END
DATE
FILMED
4-82
DTIC

MICROCOPY RESOLUTION TEST CHART

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFOSR-TR- 82-0234	2. GOVT ACCESSION NO. AD A113 073	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CONTROLLABILITY AND EVOLUTION OF COHERENT STRUCTURES IN TURBULENT WAKES		5. TYPE OF REPORT & PERIOD COVERED FINAL 1 Jan 76 - 31 Dec 80
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) JOHN L WAY RICHARD W WLEZIEN HASSAN M NAGIB		8. CONTRACT OR GRANT NUMBER(s) F44620-76-C-0062
9. PERFORMING ORGANIZATION NAME AND ADDRESS ILLINOIS INSTITUTE OF TECHNOLOGY MECHANICS & MECHANICAL & AEROSPACE ENGINEERING CHICAGO, IL 60616		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2307/A2
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BOLLING AFB DC 20332		12. REPORT DATE 1980
		13. NUMBER OF PAGES 59
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC
ELECTE
MAR 0 6 1982

E

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

WAKE STRUCTURE	TWO-DIMENSIONAL PROCESSING	THERMAL TAGGING
COHERENT STRUCTURES	FLOW VISUALIZATION	TWO-DIMENSIONAL
KARMAN VORTEX	CONVECTIVE FLOW VISUALIZATION	SPECTRAL DECOMPOSI-
LARGE SCALE STRUCTURE	LOCAL FLOW VISUALIZATION	TION
PATTERN RECOGNITION	POLYCHROMATIC SIGNAL DECOMPOSITION	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The main objectives were to answer some of the questions of evolution of large scale structure in turbulent wakes and to develop new techniques of experimentation and data reduction to identify and document the organized structures in turbulent flows. The techniques of thermal tagging, polychromatic signal decomposition, local and convective flow visualization, digital image processing and pattern recognition, two-dimensional spectral decomposition of velocity fields, as well as spatial reconstruction are applied to the bluff body wake problem. The results of these experiments have clarified the picture of wake evolution over →

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE

AD A11 3073

DTIC FILE COPY

a wide range of Reynolds numbers, from laminar to turbulent. These techniques demonstrate that an approach as elaborate as the orthogonal decomposition scheme is not necessary to objectively bring out the important large scale mechanisms. It has been shown that the large scale vortical structures shed into the near wake, i.e. the Karman vortex street, decay exponentially and that the large scale far wake structures are produced as a result of the instability of the mean wake profile downstream. The far wake structures are therefore not demonstrated over a wide range of Reynolds numbers from laminar to turbulent, as well as for bluff bodies that do not periodically shed a vortex street into the near wake (eg - porous bodies), where the evolution of the far wake structure is clearly traced in isolation through the wake instability. The study also clearly refutes the pairing mechanism active in shear layers as that responsible for the growth of the large scales. Thus, the study has documented the mechanism of large scale evolution in the turbulent flow of far wakes, answering one of the long outstanding questions in turbulence research.

CONTROLLABILITY AND EVOLUTION OF COHERENT
STRUCTURES IN TURBULENT WAKES

FINAL TECHNICAL REPORT

BY

JOHN L. WAY

RICHARD W. WLEZIEN

AND

HASSAN M. NAGIB

Accession For	
DTIC GRA&I	X
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	

DTIC
COPY
INSPECTED
2

JANUARY 1, 1976 TO DECEMBER 31, 1980

U.S. AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

CONTRACT NO. F44620-76-C-0062

DEPARTMENT OF MECHANICS AND MECHANICAL AND AEROSPACE ENGINEERING
ILLINOIS INSTITUTE OF TECHNOLOGY
CHICAGO, ILLINOIS 60616

I. RESEARCH OBJECTIVES

The primary objectives of this research effort were to answer some of
the questions of evolution of the large scale structure in turbulent wakes,
and to provide detailed data for cases on which the more sophisticated
predictive theories could be critically tested and their limitations
revealed. A secondary objective was to develop new techniques of
experimentation and data reduction to identify and document these large
scale wake structures, with the hope that the same techniques would not
only shed new light on this research topic, but would also be useful in
other research areas in fluid mechanics. Following a review of the state
of knowledge of the large scale turbulent wake structure, detailed
objectives for this research study are specified.

Interest in the large scale structure of turbulent flows has grown in
recent years, but researchers have been aware of the periodic structure in
the wake of a cylinder for about a century. Strouhal (1878) and Benard
(1908) observed the double row of vortices which formed downstream of a
cylindrical body. Von Karman and Rubach (1912) idealized the geometry of
the wake vortex structure and analyzed what is now known as the Karman
vortex street. Early experimental work on wake flow was primarily limited
to visualization, but with increased Reynolds number, turbulence and
three-dimensionality makes visualization much more difficult. Goldstein
(1938) noted that no double row of vortices had been seen or photographed
at a Reynolds number greater than 2,500 even though it was known that
eddies continued to be shed periodically at a Reynolds number as great as

500,000. Even to this date, very little has been published concerning the development of the structures in turbulent wakes.

Perhaps the earliest detailed study of the near wake using hot-wire anemometers was conducted by Kovasznay (1949). In addition to measuring the mean velocity profiles, he determined a critical Reynolds number above which vortices are shed from the cylinder. Roshko (1954) investigated the development of the wake over a wide range of Reynolds number using a single hot-wire sensor and spectrum analyzer. He found that the characteristic peak in the velocity spectrum which is due to the vortex street persisted up to about 40 diameters downstream of the cylinder for Reynolds number up to 4,000. As pointed out by Bevilaqua (1975), the periodicity may persist over much longer distances since the velocity fluctuations due to the vortex street may be primarily in the cross-wake velocity component. Roshko's single hot-wire was relatively insensitive to these fluctuations.

Morkovin (1964) classified the wake flow into several Reynolds number regimes. For the range of roughly 150 < Re < 130,000 there is transition to turbulence in the wake, with the region of transition moving closer to the cylinder with increasing Reynolds number. There is also increasing three-dimensionality, but the Karman vortices are still shed in a locally regular fashion. Recent measurements using phase conditioned averaging (Cantwell 1976, Wlezien and Way 1976, Davies 1974) have established the structure of the turbulent near wake. At least in the mean, these structures are not unlike those seen in the laminar wake. Davies cites evidence that the individual structures are more like vortex clouds that distort due to interactions with each other as they are convected downstream.

Relatively few researchers have investigated the three-dimensional

structure and the downstream development of these vortices. Hama (1957) injected dye along the span of the cylinder and found three-dimensionality in the vortex structure very near to the cylinder for Reynolds number as low as 300. On the other hand, Gerrard (1966) used an array of hot-wires oriented parallel to the cylinder axis, and for a Reynolds number of 2000 he found the axes of the individual vortices to be irregular, but in general parallel to the cylinder. Shimizu (1973) found the spanwise scale at the cylinder to be of the order of ten diameters over an extensive range of Reynolds number. In general the near wake appears to be made up of quasi-regular organized structures even when the flow is turbulent, and this is similar to what was observed by Brown and Roshko (1974) in a turbulent mixing layer.

Much experimental effort has also been devoted to the far wake, but for the most part no attempt has been made to relate the vortex street to the far wake structures. Probably the earliest evidence of structure in the turbulent far wake is Townsend's (1956) transverse velocity correlations. Based on this rather limited correlation data, Townsend proposed that a set of large eddies rotating about axes oriented in the direction of mean flow are consistent with the correlations. Grant (1957) extended Townsend's work by measuring the diagonal elements of the cross correlation tensor for spatial separations in all three coordinate directions and for several reference sensor positions. Although this is a more extensive data set than Townsend's measurements, the off-diagonal components of the correlation tensor were not measured.

Grant assumed that the large scale structures are the simplest model eddies consistent with the correlation data, especially at large spatial separations. On the basis of the u and w correlations alone, Grant devised

a bent double roller structure which is symmetric about the center of the wake, with the axes of the eddies inclined at about 45 degrees in the downstream direction. Model velocity profiles of such eddies have u and w correlations in good agreement with Grant's data, except at a zero x and large y separation, where there is a deficit in the measured correlations. The double roller model also has no v component of velocity, so it is not consistent with the damped periodicity of the v correlations in the x direction. With the help of dye flow visualization Grant proposed a second periodic "entrainment jet" structure which is consistent with the deficits and the v correlations. Obviously there is a certain amount of bias associated with choosing the model structures, but at the least the measured correlations indicate the existence of large scale organized structures.

In an attempt to be more objective about the definition of these structures in the wake, Payne and Lumley (1967) applied Lumley's orthogonal decomposition to the data obtained by Grant. This technique is based on the assumption that eddies of random spatial orientation are averaged together in the correlations, so that the correlation tensors can be decomposed into a set of eigenfunctions corresponding to the eddies. The results do show a structure very similar to that proposed by Grant, but a mixing length assumption had to be used to get the off-diagonal elements of the correlation tensor. Recent measurements by Townsend (1979) indicate that the wake structures are in fact much less random in orientation than expected and do not overlap. The orthogonal decomposition technique may thus not be rigorously applicable.

Grant (1957) and Townsend (1970) speculate on possible sources of the coherent motions. In order to study the wake structures without a mean

velocity gradient, Grant made a series of measurements in the zero gradient wake of a set of parallel cylinders. His conclusion is that the double roller structure must be formed near to the cylinder, but paradoxically the structure in the single cylinder wake is not deformed enough in the far wake to have experienced the mean shear for its entire lifetime. On the other hand, Townsend notes that the structures are very much like what would result from a rapid shearing of isotropic turbulence, hence they need not have been formed in the near wake. Instead, the near wake structures could break down into turbulent motions, and the structures observed in the far wake would be selectively amplified by the mean shear. As for the entrainment jet structure, Grant explains the quasi-regularity in terms of a stress release mechanism. The wake undergoes a non-uniform strain, which tends to make the turbulence more anisotropic. Because the anisotropy does not grow indefinitely, the turbulent stress must be released through an entrainment jet. This in turn induces a jet on the opposite side of the wake, hence the quasi-periodic structure.

Keffer (1965) strained a turbulent wake in a zero velocity gradient distortion duct and observed the effect of straining on the large eddies. When the wake is stretched in the spanwise direction and compressed in the transverse direction, visualization indicates that eddy groups occurring at from one-third to one-fourth the Strouhal frequency are selectively amplified. Keffer suggests that these structures are similar to the entrainment jets, and in fact the periodicity in Grant's v correlations are of similar scale. The fact that these structures occur quite regularly implies that they are not produced by the selective amplification of vortices in homogeneous turbulence, because such vortices would be random. Keffer suggests that the structures are formed in the near wake in a

fashion similar to the Karman vortex street but lower in frequency and much more diffuse. Visualization indicates that although the structures occur in regular groups, in general there is no correlation across the centerline of the wake. Only in the mean are there equal numbers of vortices on both sides of the wake.

Kovasznay, Kibens, and Blackwelder (1970) observed a relationship between the motion of the interface between turbulent and non-turbulent fluid and the large scale structures in a boundary layer. Similar measurements have been made in the wake to further investigate the Grant-Keffer type structures. LaRue and Libby (1974) found no evidence of continuously periodic interface motion at a nondimensional streamwise distance x/D of 400, but the intermittency autocorrelations hint at locally periodic motion. Structures with a scale of two Strouhal wavelengths and larger are highly correlated with the motion of the interface. In addition, there is strong evidence of structures having scales of from two to twenty Strouhal wavelengths which are inclined at an angle of about 31 degrees from vertical in the downstream direction.

In a subsequent paper, LaRue and Libby (1976) present a detailed study of the interface statistics. There is a short time periodicity at about one third the Strouhal frequency, and the peak interfacial crossing frequency is about one half the Strouhal frequency near the half intermittency point. This is consistent with the results of Thomas (1972) and Fabris (1974). Together the measured peak interface crossing frequencies vary from one-half to one-third the Strouhal frequency for x/D from 160 to 400. The velocity measurements of Fabris indicate an outward velocity component at the upstream boundary of the turbulent bulge, and an inward velocity at the downstream boundary, so the structures appear to be

rolled over by the non-turbulent flow, implying a large eddy structure tied to the motion of the interface.

It is tempting to try to relate these structures to those in the near wake, but two characteristics must be accounted for. The previously discussed measurements consistently show a wavenumber reduction in the far wake, and any coherent periodicity is gone. Keffer's proposal of a secondary vortex street of lower wavenumber would explain the observed far wake, but there is no evidence of that structure in the near wake. Visualization studies of wake development by Taneda (1959) and Papailiou and Lykoudis (1974) have produced conflicting results. Taneda observed the wake for 10 < Re < 1,000 and documents a repeated breakdown and rebirth of the vortex street. After each breakdown the wake rearranges itself into a vortex street of lower wavenumber. For laminar wakes the wavenumber ratio is from two to three, but for turbulent wakes the rebirth is delayed and the wavenumber ratio can be as great as ten. Papailiou and Lykoudis document a very different behavior for 1,000 < Re < 20,000. The wake vortices appear to break into smaller rotating parts which eventually separate. This is opposite of what other far wake measurements indicate because it implies an increase in wavenumber in the downstream direction. Surprisingly the vortices persist in a more or less regular pattern for several hundred diameters downstream of the cylinder, although there is a randomization of phase and vortex position. The apparent discrepancies emphasize that these visualization experiments have distinct limitations and that the results must be carefully interpreted. In both instances a liquid surface visualization technique is used, and effects such as surface tension can distort the wake. For example, an anomolous symmetric double row of vortices comprises the wake for some distance downstream of the

cylinder in some of the pictures of Papailiou and Lykoudis, whereas hot-wire measurements by other investigators show no such structure.

The visualization results are significant, however, because they imply a connection between the near and far wake. Townsend (1970) characterizes the large eddies of turbulent flow as relatively stable entities, with a single eddy enduring for quite some time even in homogeneous turbulence. The mean gradients of the flow appear to distort rather than destroy the large eddy structure. A strong candidate for the wavenumber reduction mechanism is the vortex amalgamation event observed by Winant and Browand (1974) in a shear layer. Bearing in mind that the wake dynamics are quite different from those in the shear layer, such amalgamation events would account for the increase in scale size with wake development. The wake grows much more slowly than the shear layer, and only one or two amalgamations need occur over a distance of 400 diameters to account for the measured increase in scale.

Another growth mechanism is discussed by Hinze (1975) and Roshko (1976). The long spanwise vortex filaments in the near wake can be destabilized by disturbances which deform the vortex line. Through a combination of self induction and mean shear such disturbed vortices can deform into U shaped loops. These loops might then grow into the double rollers described by Grant, but as mentioned earlier the structures observed in the far wake are not deformed enough to have experienced the mean shear all the way from the early part of the wake. Hama (1957) demonstrates that there is a randomly wavy spanwise structure for Reynolds number as low as 150, and when the Reynolds number exceeds approximately 300 the vortex line distorts almost immediately after formation and breaks down into turbulence. The formation of the vortex loop remains an open

question, especially at higher Reynolds numbers. Barsoum, Kawall, and Keffer (1978) investigated the spanwise statistics of the intermittent structure at a downstream distance of 100 diameters. They conclude that the spanwise structures are quite narrow, about one half to one third the streamwise scale, and that the structures are not bent in the spanwise, or z, direction. A close examination of their results indicates the possibility that the correlations extend further in the z direction than the range of their measurements. If the trends in their data continue beyond the range shown, there would appear to be a damped periodicity in the correlation curve, with a scale of about two Strouhal wavelengths. There is also some slight evidence of a U shaped structure, but their measurements need to be extended.

Townsend (1979) pursued the question of wake development by looking for specific structures in the far wake. By fitting models of the vortex street eddies and of Grant's double roller structure to multiple point velocity data, he has concluded that the large scale velocity patterns tend to be rather simple. The time-averaging of structures with random phase, position, and age make them appear to be much more complex. By using the vortex street models, Townsend finds periodic patterns consisting of groups of from three to five eddies at an x/D of 170. These groups have a relatively regular eddy structure within them, but the variability between these groups is large. Even though the internal structure of a particular group is periodic at the Strouhal frequency, a correlation which averages over many of these structures can exhibit a significantly lower characteristic wavenumber.

Townsend (1979) also computed weighted correlations where structures which contribute most to the turbulent intensities within a volume have the

greatest weighting. The double roller model fits the correlation data better when such weighting is used, so Townsend concludes that these structures contain most of the turbulent energy. A drawback of this method is that the measurements rely on a predetermined model, and in this sense they are biased. More recent efforts employ a heuristic scheme to determine the model structures directly from the data.

Considering the state of knowledge as reviewed above, it was decided to begin the research with a careful experimental documentation of the near wake structure for a circular cylinder over a Reynolds number range from 5,000 to 10,000. After the near wake structure had been documented, the focus was to move downstream in an attempt to understand how the near wake is modified to produce the mid wake region, and how this region evolves into the far wake. The existence of regular large-scale structures in the near wake has been well established and large-scale motions have also been documented in the self-preserving far wake. The periodicities found in the early part of the wake development are known to decay with increasing streamwise distance, and the connection between these structures and those found in the far wake remains to be determined. Pairing events have been documented in mixing layers and jets and it is an open question as to whether such a mechanism contributes to the wake growth, although other research has suggested a breakdown-rebirth mechanism for the increase in wake scales.

In the subcritical regime, which is the Reynolds number range of current interest, the basic wake characteristics have a very weak dependence on Reynolds number. A single Reynolds number of 5000, which was judged to be typical of the regime, is used for the primary experiment, and measurements are made for a range of streamwise locations. Although the

investigation of Reynolds number dependence appeared to be worthwhile, it is often difficult to separate these effects from the effect of changes in the free-stream disturbance level.

A secondary objective was to develop measurement schemes which are well suited to the investigation of organized structures in turbulent flows. Flow visualization techniques which have been applied to various other fluid mechanics problems are not necessarily best for the observation of these organized turbulent structures. Techniques which employ spatial averaging would appear to be better suited to this task.

The application of two-dimensional processing to turbulence measurement appears to hold promise for the identification of instantaneous large-scale organized structures. For more common techniques in which ensemble averaging is used, the conflicting requirements of objectivity and selectivity have reduced their usefulness. The spectral approach to turbulence is an objective way to define these structures, and the ability to instantaneously extract the large-scales from the background flow avoids many of the pitfalls of the ensemble techniques.

II. RESEARCH EFFORT

The fundamental objective of the present study was defined as the investigation of the evolution of the large-scale structures which have been observed in turbulent wakes. The need for unbiased methods for the measurement of such structures was also established and this was adopted as a second basic objective of this investigation. The consequences of measurement and processing techniques developed during the program will be discussed here.

Detailed measurements of the near wake of a circular cylinder in crossflow were made over a Reynolds number range from 5800 to 10,600. The attached boundary layer on the cylinder was tagged with heat and this thermal tracer was subsequently detected downstream in the near wake, as described by Wlezien and Way (1976). Phase averaged mean and fluctuating indications of vorticity behind the circular cylinder have been computed and output as isometric surface plots. A 16 mm motion picture of the variation of these surface plots with phase was generated and clearly shows the formation of an "average" Karman vortex and its subsequent motion downstream. This led to a new definition of the formation length, an important parameter of the near wake region. The variation of formation length with Reynolds number was documented over the range of the experiment. The resistance thermometer circuit used in conjunction with the thermal tagging technique was one of a family of 24 such circuits analyzed by Wlezien and Way (1977) for sensitivity, linearity, and other important operating parameters. A new technique for extraction of both amplitude and phase modulation of the eddy shedding process, reported in

Wlezien and Way (1979), was developed for this study and has been shown to provide better phase conditioning than previous methods. The technique involves a numerical method of extracting instantaneous amplitude and phase information from a polychromatic signal, and its application to other research areas should be useful. For the near wake data, amplitude and frequency statistics of the instantaneous phasing signal were computed.

A detailed study was completed on temperature compensation of hot-wire and hot-film sensors and is detailed by Drubka, Tan-atichat and Nagib (1977). A new technique for computing turbulent integral time scales with increased accuracy was developed and presented by Nagib, Wigeland and Wlezien (1978). The method removes unwanted contributions to the rms and integral scale parameters due to finite record length and non-turbulent low frequency tunnel fluctuations.

The concept of large-scale structures in turbulence has become widely accepted in the past several years, and the definitions of these structures appears to be as diverse as the flows in which they have been measured. The apparent contradiction between selectivity and objectivity in schemes which utilize ensemble averaging techniques is discussed by Lumley (1981) and encourage the use of a spectral approach to large-scales in turbulence. In the classical Reynolds' decomposition, the turbulent velocity field is reduced to mean and fluctuating components, and this view of turbulence has pervaded the experimental studies. In the modern view of turbulence, it appears to be more meaningful in terms of the physics of the flow to decompose the velocity field into large-scale and small-scale components, where the various scales are defined in the spectral sense. This decomposition is used in the "large-eddy simulation" of turbulence (Ferziger and Leslie 1979), and a similar approach is applied here to

instantaneous two-dimensional flow measurements.

A major stumbling block in such measurements is the development of an instrument which can define the instantaneous multi-dimensional velocity field. In the work reported here, as described by Wlezien (1981), the spectral approach can be used to advantage because only a relatively small amount of information is required to uniquely describe the largest scales in the flow. Just as the discrete samples of a properly digitized signal contain enough information to completely define the original function, so too can a proper spatial sampling be used to completely define the large structures. In this way, sparse hot-wire measurements which are obtained at relatively low sampling rates can be used to determine the space-time development of turbulent structures.

Although only eight velocity sensors were used in the present experiment by Wlezien (1981), the instantaneous streamwise velocity field was measured and reconstructed for the typical large structures in the vortex street and the far wake. The limitation of this experiment to a single component of velocity was not a consequence of the reconstruction scheme, and as such the computations can be easily extended to multiple velocity components. The primary limitation in this respect is the difficulty of operating a number of multiple sensor probes, but it is hoped that extentions to two or even three velocity components can be implemented in later experiments.

The characteristics of various two-dimensional filters were determined using a sample set of velocity data, and problems associated with stopband leakage and filter sharpness were investigated. In general, the stopband ripple can cause severe output distortion problems, and minimal ripple lowpass filters with wide transition bands produced the most satisfactory

results. It was found that the filters must be optimized to a particular application, with the filter shape being based on the two-dimensional spectrum of the velocity data.

Although the spatial reconstruction technique is necessarily more complex than other more commonly used methods, the ability to make unbiased measurements of the instantaneous large-scales in a turbulent flow more than compensates for this complexity. With proper caution, one-dimensional reconstruction filters can be designed using optimization routines such as that developed by McClellan et al.(1973) and converted to two-dimensional filters using transformation techniques.

As a supplement to the direct flow measurements, visualization pictures were obtained to provide further insight into the global wake behavior. When standard visualization techniques are applied to the measurement of coherent structures in turbulence, the results are often difficult to interpret, and the Lagrangian technique developed by Wlezien (1981) was designed to avoid these shortcomings. In particular, conventional visualization techniques suffer from flow history effects, and these were minimized by introducing the smoke tracer locally in the wake, rather than far upstream or at the cylinder. Short time exposures were used to effectively filter out small scale motions, and the wake structures were effectively observed in their rest frame by following their motion with a rotating mirror.

The visualization photographs obtained using this technique proved to be much more suited to the detection of large-scale structure in the flow. Instantaneous photographs tend to emphasize the small-scale structure of the turbulence and the motion of the turbulent-nonturbulent interface, whereas the Lagrangian visualization proved to be much more sensitive to

the large-scale wake motions.

The effect of cylinder end conditions was also investigated by Wlezien (1981) using both visualization and hot-wire velocity measurements. It was found that the interaction between the wake and wind-tunnel sidewall boundary layers results in significant wake distortion across the entire span of the cylinder, even for aspect ratios as great as 85. The vortex shedding frequency decreases as the sidewall is approached, and this variation is accomodated by sharp changes in the wake vortex lines. The wake vortices appear to exist in two stable modes: continuous vortex lines, and 180 degree dislocations. This bimodal behavior can account for low spanwise velocity correlations in the wake, and the resultant spanwise cellular structure of the wake can lead to self-induced motions and vortex breakdown. When end-plates were added at a Reynolds number of 5000, the spanwise wake structure became significantly more homogeneous, although the same endplates did little to uniformize the wake at higher Reynolds number. It would appear that the end effects, which to a large extent have been ignored in previous experiments, play a significant role in the development of the wake and the common practice of extending the cylinder to obtain a large aspect ratio does not seem to be sufficient to eliminate spanwise distortions. The wake periodicities measured in the present investigation were found for longer streamwise distances than those found by Roshko (1954) and Budny et al. (1979), and it appears that this persistence is associated with the reduced sidewall interactions of the present study.

The mechanism of the decay of the wake periodicity is central to the study of wake evolution. A well-accepted point of view is that the periodic vortices decay due to turbulent diffusion as they are convected downstream and the spectral results indicate an exponential decay of the

wake vortices.   It appears that a more appropriate approach might be to ask what happens to the wake periodicity and then ask what happens to the structures which originally made up the vortex street.

The inter-structure statistics which were computed by Wlezien (1981) for the reconstructed velocity field indicate that there is an abrupt change in the periodicity of the vortices as they are convected over the first 20 diameters downstream from the cylinder. A frozen field assumption would indicate that the periodicity should exist for a much longer distance. However, the wake appears to quickly reorganize after its initial formation. Visualization indicates that the periodicity which does persist is due to intermittent groups of periodic vortices which happen to exist for longer downstream distances.

The mechanism by which the near-wake structures lose energy and randomize appears to be related to the vortical umbilical connection between successive structures. Cantwell (1981) notes that the turbulent Reynolds stresses are greatest here and visualization demonstrates that the interaction of the counter-rotating vortices and the mean shear can act so as to transfer turbulent energy to this vortical fluid.

In the work of Wlezien (1981), the fast decay of the near-wake structures is evident in the reconstructed velocity with the mean shear retained. At 10 diameters, the velocities in these vortices are of the same order as the mean shear, and the regular wake structure is apparent even when superposed on the mean shear. As the streamwise distance increases, these structures weaken much faster than the mean shear, so that when the shear is retained in the measured data, it dominates all other components of the velocity field. The results of Cimbala et al. (1981) suggest that energy is actually being transferred from the vortical

structures to the mean shear, and that these structures cannot persist away from the cylinder.

It was observed that the exponential decay of the near wake periodicity is an indication that such structures can exist only in the vicinity of the wake-forming body. As reported by Wlezien (1981), the present results show a similar decay, although it appears to be due both to a general decrease in vortex strength and a randomization in structure spacing. There is evidence that remnants of these structures continue to exist far from the cylinder, although these vortices are extremely weak in comparison with the mean shear.

The large structures which exist in the wake away from the cylinder appear to be the result of local instabilities in the mean shear and are not directly related to the near wake. Visualization indicates the presence of elongated vertical structures near the edge of the wake for streamwise distances greater than about 40 diameters. Further measurements verify the existence of such elongated structures, and the growth in structure scales and spacing suggest that the wake undergoes a transformation soon after it is formed.

These results tend to favor certain viewpoints discussed in Section I. There is no question of the periodic structure in the early wake, although previous results such as Cantwell (1976) and Wlezien and Way (1976) relied on periodic averaging to determine the wake structure. The instantaneous results and visualization obtained here demonstrate the overall regularity of the near wake, although there is an occasional loss of periodicity even at an x/D of 10. This could explain why the intermittency did not go to unity at the center of Cantwell's conditionally averaged structures.

The results obtained by Grant (1957) tend to emphasize the

three-dimensional structure of the wake, and suggest that the fundamental structure is normal to the plane of the wake. Discontinuities in the wake structures which result from improper cylinder end conditions have been documented here, and it has been shown that such discontinuities can lead to problems in correlation-type measurements. Although the present measurements have been obtained in a plane normal to the cylinder and as such will not be sensitive to the Grant-type structures, the results are consistent with the entrainment jets observed visually by Grant. Keffer (1965) documented structures similar to the entrainment jets, although he suggests that they were formed in the near wake along with the vortex street. His results are completely consistent with the present measurements.

Roshko (1954) and Budny, Kawall, and Keffer (1979) measured the decay of the discrete spectral peak with increasing streamwise distance, and although the careful end conditions appear to help preserve this regular structure, the present results show the same general decay. The periodic structures do in fact appear to be disappearing in the first 80 diameters of the wake evolution, and this is quite contrary to the long term regularity observed by Papailiou and Lykoudis (1974). In fact the regularity in the structure positions breaks down very early and the structures themselves decay rapidly over the first 80 diameters of wake development.

In general, the vortex amalgamation events observed by Winant and Browand (1974) in a mixing layer do not appear to be applicable to the alternating wake structure. Instead, the interaction of these oppositely rotating vortices with the mean shear produces a mechanism which leads to their ultimate destruction. As Cantwell (1981) notes, the vortical fluid

which is stretched between the periodic structures is a primary source of fluctuating Reynolds stress, and this stretched vorticity appears to be extracting energy from the near wake structures. Cimbala, Nagib and Roshko (1981), in work partly supported by this research project, indicate a similar mechanism. A combination of local smoke-wire flow visualization and hot-wire anemometry was used to show that the near wake vortex street decays exponentially within the first 50 to 100 diameters. It is documented that a secondary vortex street exists beyond 100 diameters for a wide range of Reynolds numbers, and it is proposed that the mechanism responsible for this larger scale structure is the instability of the mean wake profile.

CONCLUSIONS

For the first time, the techniques of thermal tagging, polychromatic signal decomposition, local and convective flow visualization, digital image processing and pattern recognition, two-dimensional spectral decomposition of velocity fields, as well as spatial reconstruction are all applied to the bluff body wake problem, see Wlezien and Way (1976), Nagib, Corke, Helland and Way (1978) and Wlezien (1981). The results of these experiments have clarified the picture of wake evolution over a wide range of Reynolds numbers, from laminar to turbulent. These techniques demonstrate that an approach as elaborate as the orthogonal decomposition scheme of Lumley (1981) is not necessary to objectively bring out the important large scale mechanisms. It has been shown that the large scale vortical structures shed into the near wake, i.e. the Karman vortex street, decay exponentially and that the large scale far wake structures are produced as a result of the instability of the mean wake profile downstream. The far wake structures are therefore not directly related to the near wake structures. This has been amply demonstrated here by Cimbala, Nagib and Roshko (1981) over a wide range of Reynolds numbers from laminar to turbulent, as well as for bluff bodies that do not periodically shed a vortex street into the near wake (eg - porous bodies), where the evolution of the far wake structure is clearly traced in isolation through the wake instability. They also clearly refute the pairing mechanism

active in shear layers as that responsible for the growth of the large scales as had been proposed by Matsui and Okude (1981). Thus, the study has documented the mechanism of large scale evolution in the turbulent flow of far wakes, answering one of the long outstanding questions in turbulence research. Some of these conclusions resulted from a unique collaborative effort in two laboratories, one at I.I.T. and the other at C.I.T.

III. LIST OF MANUSCRIPTS

1. Wlezien, R. and J. L. Way, "An Experimental Investigation of the Near Wake of a Circular Cylinder in the Subcritical Regime," I.I.T. Fluids and Heat Transfer Report R76-3; Technical Report, AFOSR-TR-78-1292.

2. Wlezien, R. W. and J. L. Way, "Bridge Circuits for Differential Resistance Measurement and their Application to Resistance Thermometry," International Congress on Instrumentation in Aerospace Simulation Facilities Record, IEEE publ. 77CH 1251-8 AES, 1977.

3. Drubka, R. E., J. Tan-atichat and H. M. Nagib, "Analysis of Temperature Compensating Circuits for Hot-wires and Hot-films," DISA Information, 22, December, 1977.

4. Nagib, H. M., T. C. Corke, J. L. Way and K. N. Helland, "Computer Analysis of Flow Visualization Records Obtained by the Smoke-wire Technique," Proc. Dynamic Flow Conference 1978, Johns Hopkins University, Baltimore, Md., September, 1978.

5. Wlezien, R. W. and J. L. Way, "Techniques for the Experimental Investigation of the Near Wake of a Circular Cylinder," AIAA Jour., 6, pp 563-570, June, 1979.

6. Wlezien, R. W., "The Evolution of the Low Wavenumber Structure in a Turbulent Wake," Ph.D. Thesis, Illinois Institute of Technology, 1981; also appears with J. Way as I.I.T. Fluids and Heat Transfer Report R81-4; Technical Report, AFOSR-TR-81-   .

7. Cimbala, J., H. M. Nagib and A. Roshko, "Wake Instability Leading to New Large Scale Structures Downstream of Bluff Bodies," submitted to Phys. of Fluids, 1982.

IV. SCIENTIFIC PERSONNEL

John L. Way, Associate Professor
     Co-Principal Investigator

Hassan M. Nagib, Professor
     Co-Principal Investigator

Mark V. Morkovin, Professor
     Internal Consultant

Jimmy Tan-atichat, Visiting Assistant Professor
     Internal Consultant

Richard W. Wlezien, Research Assistant
     M.S. Degree; Thesis Title: An Experimental Investigation of the Near
               Wake of a Circular Cylinder in the Subcritical Regime,
               May, 1976.
     Ph.D Degree; Thesis Title: The Evolution of the Low Wavenumber
               Structure in a Turbulent Wake, December, 1981.

Dennis J. Koga, Research Assistant
     Ph.D Degree Candidate

Thomas C. Corke, Research Assistant

Robert E. Drubka, Research Fellow

V. PRESENTATIONS

1. Wlezien, R. W., presented a seminar at Illinois Institute of Technology entitled "An Experimental Investigation of the Near Wake of a Circular Cylinder in the Subcritical Regime," May, 1976.

2. Way, J. and R. Wlezien, "Phase Conditioned Measurements in the Near Wake of a Circular Cylinder," 29th Physics of Fluids Meeting of the American Physical Society; abstract appears in APS Bulletin, November 1976.

3. Wlezien, R. and J. Way, "Reynolds Number Dependence of the Near Wake of a Circular Cylinder," 30th Physics of Fluids Annual Meeting of the American Physical Society; abstract appears in APS Bulletin, November, 1977.

4. Way, J. L., presented a seminar at Northwestern University entitled "Conditionally Sampled Measurements in the Near Wake of a Circular Cylinder," January, 1978.

5. Way, J. L., and R. W. Wlezien, "Techniques for the Experimental Investigation of the Near Wake of a Circular Cylinder," presented at the AIAA 11th Fluid and Plasma Dynamics Conference, Seattle Washington, July, 1978.

6. Way, J. L., presented a seminar at Illinois Institute of Technology entitled "Quantitative Analysis of Flow Fields Using Visualization and Digital Image Processing Techniques," October, 1978.

7. Corke, T. and Y. Guezennec, "Phase Conditioned Visualization of the Near Wake of a Circular Cylinder Using the Smoke-wire Technique," 31st Physics of Fluids Meeting of the American Physical Society; abstract appears in APS Bulletin, November, 1978.

8. Nagib, H. M., R. A. Wigeland and R. W. Wlezien, "Signal Processing Techniques Applicable to Three-Dimensional and Periodic Flows," 31st Physics of Fluids Annual Meeting of the American Physical Society; abstract appears in APS Bulletin, November, 1978.

9. Drubka, R. E. and R. W. Wlezien, "Efficient Velocity Calibration and Yaw-Relation Truncation Errors in Hot-wire Measurements of Turbulence," 32nd Physics of Fluids Annual Meeting of the American Physical Society; abstract appears in APS Bulletin, November, 1979.

10. Wlezien, R. W., presented a seminar at Illinois Institute of Technology entitled "The Evolution of the Low Wavenumber Structure in a Turbulent Wake," May, 1981.

11. Cimbala, J., H. M. Nagib and A. Roshko, "Wake Instability Leading to New Large Scale Structures and Downstream of Bluff Bodies," 34th Physics of Fluids Annual Meeting of the American Physical Society;

abstract appears in APS Bulletin, November, 1981.

12. Wlezien, R. W. and J. L. Way, "The Evolution of the Low-Wavenumber Structure in a Turbulent Wake," 34th Physics of Fluids Annual Meeting of the American Physical Society; abstract appears in APS Bulletin, November, 1981.

13. Koga, D. J., R. W. Wlezien and J. L. Way, "Reconstruction and Processing Techniques for Sparsely Sampled Low-Wavenumber Structures," 34th Physics of Fluids Annual Meeting of the American Physical Society; abstract appears in APS Bulletin, November, 1981.

VI. BIBLIOGRAPHY

Barsoum, M., Kawall, J., and Keffer, J. 1978. Spanwise Structure of the Plane Turbulent Wake. Phys. Fluids 21, 157-161.

Benard, H. 1908. Formation de centres de giration en arriere d'un obstacle en mouvement. C. R. Acad. Sc., 147, 839-842.

Bevilaqua, P. 1975. Intermittency, the Entrainment Problem. ARL Technical Report 75-0095, Aerospace Research Laboratories, United States Air Force.

Budny, J., Kawall, J., and Keffer, J. 1979. Vortex Street Evolution in the Wake of a Circular Cylinder. Second Symposium on Turbulent Shear Flows, Imperial College, London.

Brown, G. and Roshko, A. 1974. On Density Effects and Large Structures in Turbulent Mixing Layers. J. Fluid Mech. 64, 775-816.

Cantwell, B. 1976. A Flying Hot-Wire Study of the Turbulent Near Wake of a Circular Cylinder at a Reynolds Number of 140,000. Ph.D. Thesis, California Institute of Technology.

Cantwell, B. 1981. Organized Motion in Turbulent Flow. Ann. Rev. Fluid Mech., 457-515.

Cimbala, J., Nagib, H., and Roshko, A. 1982. Wake Instability Leading to New Large Scale Structures Downstream of Bluff Bodies. submitted to Phys. of Fluids.

Davies, M. 1974. A Comparison of the Wake Structure of a Stationary and Oscillating Bluff Body, Using a Conditional Averaging Technique. J. Fluid Mech. 75, 209-231.

Drubka, R. E., Tan-atichat, J. and Nagib, H. M. 1977. Analysis of Temperature Compensating Circuits for Hot-wires and Hot-films. DISA Information.

Fabris, G. 1974. Conditionally Sampled Turbulent Thermal Velocity Fields in the Wake of a Warm Cylinder and its Interaction with an Equal Wake. Ph.D. Thesis, Illinois Institute of Technology.

Ferziger, J.H. and Leslie, D.C. 1979. 'Large Eddy Simulation': a Predictive Approach to Turbulent Flow Computation. AIAA Paper No. 79/1471.

Gerrard, J. 1966. The Three-dimensional Structure of the Wake of a Circular Cylinder. J. Fluid Mech. 25, 143-164.

Goldstein, S. 1938. Modern Developments in Fluid Dynamics. Dover Publications, New York.

Grant, H. 1957. The Large Eddies of Turbulent Motion. J. Fluid Mech.

4, 149-198.

Hama, F. 1957. Three-dimensional Vortex Pattern Behind a Circular
    Cylinder. J. Aero. Sciences 24, 156-158.

Hinze, J. 1975. Turbulence. McGraw-Hill, New York.

Keffer, J. 1965. The Uniform Distortion of a Turbulent Wake. J. Fluid
    Mech. 22, 135-159.

Kovasznay, L. 1949. Hot-wire Investigations of the Wake Behind
    Cylinders at Low Reynolds Numbers. Proc. Roy. Soc. (London),
    ser A, 198, 174-190.

Kovasznay, L., Kibens, V., and Blackwelder, R. 1970. Large-scale
    Motion in the Intermittent Region of a Turbulent Boundary Layer.
    J. Fluid Mech. 41, 283-325.

LaRue, J. and Libby, P. 1974. Temperature and Intermittency in the
    Turbulent Wake of a Heated Cylinder. Phys. Fluids 17, 873-879.

LaRue, J. and Libby, P. 1976. Statistical Properties of the Interface
    in the Turbulent Wake of a Heated Cylinder. Phys. Fluids 19,
    1864-1875.

Lumley, J. L. 1981. Coherent Structuresin Turbulence. in Transition
    and Turbulence, R. E. Meyer, ed., Academic Press.

Matsui, T. and Okude, M. 1981. Vortex Pairing in a Karman Vortex
    Street. Miejo Univ., Yagato, Tenpaku, Nagoya 468, Japan.

McClellan, J. 1973. The Design of Two-dimensional Digital Filters
    by Transforms. Proc. of the 7th Annual Princeton Conference on
    Information Sciences and Systems, 247-251.

Morkovin, M. 1964. Flow Around a Circular Cylinder - A Kaliedoscope
    of Challenging Fluid Phenomena. Symposium on Fully Separated
    Flows, ASME, New York.

Nagib, H. M., Corke, T. C., Helland, K. N. and Way, J. L. 1978.
    Computer Analysis of Flow Visualization Records Obtained by
    the Smoke-Wire Technique. Proceedings of the Dynamic Flow
    Conference 1978.

Nagib, H. M., Wigeland, R. A. and Wlezien, R. W. 1978. Signal Processing
    Techniques Applicable to Three-Dimensional and Periodic Flows.
    31st Physics of Fluids Annual Meeting of the American Physical
    Society.

Papailiou, D. and Lykoudis, P. 1974. Turbulent Vortex Streets and
    the Entrainment Mechanism of the Turbulent Wake. J. Fluid Mech.
    62, 11-31.

Payne, F. and Lumley, J. 1967. Large Eddy Structure of the Turbulent
    Wake Behind a Circular Cylinder. Phys. Fluids Supplement,
    S194-S196.

Roshko, A. 1954. On the Development of Turbulent Wakes from Vortex
    Streets. NACA Tech. Rept. 1191.

Roshko, A. 1976. Structure of Turbulent Shear Flows: A New Look.
    AIAA J. 14, 1349-1357.

Shimizu, K. 1973. Spanwise Correlation in the Wake of a Circular
    Cylinder. J. Science Hiroshima Univ., Ser A 37, No. 1.

Strouhal 1878. Uber eine besondere Arc der Tonerregung. Ann. Phys.
    und Chemie 5, 216-251.

Taneda, S. 1959. Downstream Development of the Wakes Behind Cylinders.
    J. Physical Soc. Japan 14, 843-848.

Thomas, R. 1972. Conditional Sampling and Other Measurements in a
    Plane Turbulent Wake. J. Fluid Mech. 57, 549-582.

Townsend, A. 1956. The Structure of Turbulent Shear Flow. Cambridge
    University Press.

Townsend, A. 1970. Entrainment and the Structure of Turbulent Flow.
    J. Fluid Mech. 41, 13-46.

Townsend, A. 1979. Flow Patterns of Large Eddies in a Wake and in
    a Boundary Layer. J. Fluid Mech. 95, 515-537.

Von Karman, T. and Rubach, H. 1912. Uber den Mechanismus des
    Flussigkeits und Luftwiderstandes. Phys. Zs. 13, 49-59.

Winant, C. and Browand, F. 1974. Vortex Pairing: the Mechanism of
    Turbulent Mixing-layer Growth at Moderate Reynolds Number.
    J. Fluid Mech. 63, 237-256.

Wlezien, R. and Way, J. 1976. An Experimental Investigation of the
    Near Wake of a Circular Cylinder in the Subcritical Regime.
    Fluids and Heat Transfer Report R76-3, Illinois Institute of
    Technology.

Wlezien, R. W. and Way, J. L. 1977. Bridge Circuits for Differential
    Resistance Measurement and their Application to Resistance
    Thermometry. IEEE publ. 77CH 1251-8 AES.

Wlezien, R. and Way, J. 1979. Techniques for the Experimental
    Investigation of the Near Wake of a Circular Cylinder. AIAA J.
    17, 563-570.

APPENDIX

Enclosed is a preliminary copy of a manuscript by Cimbala, Nagib and
Roshko which has been submitted to the Physics of Fluids.

WAKE INSTABILITY LEADING TO NEW

LARGE SCALE STRUCTURES DOWNSTREAM OF BLUFF BODIES

J. Cimbala[*]

H. Nagib[+]

A. Roshko[+]

Aeronautics Department
California Institute of Technology
Pasadena, California
November 1981

Abstract

The rapid decay, within the first 50 to 100 diameters of vortices shed into the wake of circular cylinders is documented with smoke-wire visualization techniques and hot-wire anemometry for $70 < Re_d < 2000$. Evolution of new large scale (lower wave number) structures is observed downstream of that region. A pairing mechanism for the growth of such structures, as proposed by some authors, is not observed, but rather it appears that the new structures result from instability characteristics of the developing mean wake profile. In a related experiment the generation of large structures was observed downstream of porous flat plates ($Re_D = 7000$), which do not initially shed large structures into the wake.

---

[*]Graduate Student, California Institute of Technology.

[+]Professor, Illinois Institute of Technology

[+]Professor, California Institute of Technology

Nomenclature

d	circular cylinder diameter
D	width of flat plate
f_s	frequency of the shed vortices
$f_{s/2}$	sub-harmonic of shedding frequency
f_w	wake frequency
f_{2w}	first harmonic of wake frequency
Re	Reynolds number $\equiv \dfrac{Ud}{\nu}$
u'	rms velocity fluctuations
u'_f	rms velocity fluctuations filtered to frequencies near f
U	freestream velocity
x	downstream distance from cylinder axis
y	distance normal to cylinder axis
ν	kinematic viscosity of air

Introduction

A tremendous amount of research has been done on the near wakes of circular cylinders. Wlezien [1] offers an excellent historical summary of this experimental effort. The existence of a Karman vortex street just downstream of a circular cylinder has been well documented for all Reynolds numbers greater than 40. Some large scale motions, always of larger scale than that of the vortex street, have also been found in the far wake. Townsend [2] and Grant [3] for example have shown the existence of three-dimensional structures in the turbulent far wake; while for laminar wakes, Taneda [4] and Matsui [5] have observed a secondary two-dimensional vortex street, with the stream-wise distance between vortices from 2 to 3 times larger than that of the primary vortex street.

The relationship between the primary vortex street and the far wake structures has not yet been satisfactorily documented, although there have been several suggestions. In particular, for circular cylinder wakes at Reynolds numbers between 100 and 160, Matsui [6] has suggested a pairing mechanism for the development of the secondary vortex street. This explanation, however, does not agree with experimental data. Consider Figure 1 which shows the ratio of streamwise distance between consecutive vortices in the secondary street to that in the primary street as a function of Reynolds number [5]. If pairing was the correct mechanism for the change of scale, the ratio a_2/a_1 should be exactly 2 for all Reynolds numbers. In fact a_2/a_1 shows an inverse Re relationship and is only 2 at one Reynolds number. This type of behavior suggests that the secondary vortex street scale

depends on Reynolds number, and is independent of the scale of the
original street.

The experiments recorded here were conducted with the objective
of explaining the development of the secondary vortex street. Results
are primarily from flow visualization utilizing the smoke-wire technique
of Corke et al. [7]; conventional hot-wire anemometry was also used.

Flow visualization,though a very useful tool in research, can often
be quite misleading. For example, dye or smoke filaments in a flow are
distorted as they travel downstream, and the pattern seen at some
downstream location contains integrated information all the way back
to the point of introduction. In order to visualize the true nature
of the flow at a given location, it is desirable to introduce the flow
tracer at that location only. Traditionally the hydrogen bubble
technique in water has been useful because of this advantage; the smoke-
wire technique in air is analogous [7] and has been employed here.

As a case in point consider the two-dimensional Karman vortex
street in the wake of a circular cylinder at low Reynolds number.
Figure 2 shows a series of photographs taken at progressively
increasing downstream locations in the wake at Re = 77 , the flow
being from left to right, with the cylinder axis perpendicular to the
plane of view. In each case the smoke-wire has been placed at the
left-most edge of the field of view, and the photographs are aligned
such that any vertical line passes through the same downstream location
in all of the photographs. In photo a) the smoke-wire location is just
downstream of the cylinder; the vortex street is clearly marked, and
remains visible to the downstream end of the photograph (x/d = 400).

From photo a) alone one might incorrectly conclude that vortices are
still strong at such large downstream distances. In photos b) and c)
the smoke-wire was moved downstream to 39 and 78 diameters, respectively.
The vortices are seen to be much weaker at these positions than it would
appear from photograph a) alone. In photo d) the wire is at $x/d = 116$
and all the streaklines are parallel, which implies that the street
at this downstream location is so weak it can not be detected by the
smoke-wire technique. This essentially parallel wake profile continues
downstream with no evidence of any discrete vortices all the way to
700 diameters. The integration effect described above is clearly
demonstrated by comparing the flow pattern observed at $x/d = 300$
in each of the photographs; the pattern is drastically different,
depending on the smoke-wire location. One must therefore conclude
that by placing the smoke-wire at some location in the wake, the true
nature of the flow at that location is visualized, without the confusing
integration effect from upstream conditions.

Experimental Setup

The experiments were conducted in an open return low turbulence
wind tunnel with a test section 50 cm square and 2 meters long; the
wind velocity was variable from 50 cm/sec to 1200 cm/sec. The
turbulence level was less than 0.4%, half of which was due to a very
low frequency screen vibration in the settling chamber. The circular
cylinders used in the experiments varied in diameter from 0.06 cm to
0.5 cm, giving a Reynolds number range from 70 to over 2000. (Reynolds
number being defined as $Re = Ud/\nu$.) The cylinders spanned the test

section such that their length was 50 cm, and were stretched tightly by fasteners outside the tunnel walls. Drill rod was used to provide the maximum stiffness.

In addition to circular cylinders, porous flat plates were also stretched across the test section. The plates were approximately 2 cm in width and were aligned to face the flow broad-side; Reynolds numbers based on width ranged from 3000 to 9000. The plates were cut from screens with solidities of 29% and 47%.

The smoke-wire used for flow visualization was a 0.13 mm diameter wire of about 45 cm length, stretched vertically and supported such that it could be placed at any desired position in the wake. After the wire was coated with oil a current was passed thorugh it causing the oil to smoke. A Pentax ME super camera was electronically triggered, along with a strobe flash, to record the event on film. For further detail concerning the smoke-wire technique see Reference 7.

Freestream tunnel velocities were measured with a pitot-static tube an an electronic Barocell manometer. Fluctuating velocities were measured with a single platinum hot-wire aligned parallel to the cylinder, with its support strut angled at 45° to minimize interference. The hot-wire was mounted on a two-axis traversing mechanism which could be traversed in the flow direction (x) as well as normal to the cylinder axis (y). Output from the hot-wire anemometer was linearized with a Disa type 55 D 10 linearizer such that its output could be read in meters per second. Mean velocity profiles could then be recorded on a Hewlett-Packard x-y plotter by continuously traversing the probe normal to the cylinder axis. Rms velocity profiles could similarly be obtained

by first passing the signal through a Disa type 55 D 35 rr⁻ unit.
Ithaco 4213 electronic filters were used to measure rms velocity
fluctuations within a desired frequency band. The linearizer output
was also sent to an EMR 1510 Schlumberger spectrum analyzer to obtain
spectra of the velocity fluctuations; output from the spectrum analyzer
was recorded on the Hewlett-Packard x-y plotter.

Results

An immediate observation, by placement of a smoke-wire at different
downstream locations in the wake of a circular cylinder, is the very
rapid decay of the primary vortex street, as evidenced in Figure 2 for
Re = 77. As was discussed in the introduction the primary vortex street
is quite weak at approximately 100 diameters, leaving essentially a
parallel wake profile. The rapid decay of the shed vortices was found
to exist at all Reynolds numbers tested and is thought to be due to
viscous diffusion as well as transfer of energy from the vorticies into
the mean shear. The downstream wake profile is incompatible with, and
therefore can not support discreet vorticity at the shedding frequency.

A secondary vortex street [4, 5] can be seen at roughly 100 to
300 diameters downstream of the circular cylinder at Reynolds numbers
between 100 and 160. Some examples are shown in Figures 3, 4, and 5
at Re = 100, 129, and 156, respectively. The first two of these
figures show a very weak secondary vortex street which starts at roughly
300 diameters. The ratio of streamwise distance between the secondary
vortices to that between the primary vortices (a_2/a_1) is approximately
1.8 at Re = 100 and 2.7 at Re = 129. In Figure 5 at Re = 156 the
secondary street appears much earlier in the wake $(x/d \approx 150)$ and is

also much stronger. In this case a_2/a_1 is approximately 2. From photographs at other Reynolds numbers (not shown), a_2/a_1 was found to be 2.4 at Re = 146 and 2.3 at Re = 108. All these values agree fairly well with the data in Figure 2 except at Re = 100. The reason for this discrepancy is unknown. It was found that for all Reynolds numbers with a_2/a_1 not close to 2, the secondary street is sufficiently weaker than it is at Reynolds numbers with a_2/a_1 close to 2.

It is important to note that at all the above Reynolds numbers the primary street has decayed sufficiently by 100 diameters so that the secondary vortex street has emerged from an essentially parallel wake profile, with a scale independent of that of the primary street. Thus the following conclusion may be drawn:

After the rapid decay, within the first 50 to 100 diameters, of vortices shed into the wake of a cicrular cylinder, a subsequent new vortex street appears beyond 100 diameters at Reynolds numbers between 100 and 160. The new structures result from instability characteristics in the shear of the developing mean wake profile; small disturbances of certain wave numbers are amplified, eventually forming a new vortex street whose scale is independent of the original scale and depends only on the shape of the wake profile and the Reynolds number. The secondary vortex street is strongest, however, when the ratio of secondary scale to primary scale is near 2.

A Reynolds number of 155 was chosen for detailed hot-wire measurements to support this conclusion. Rms velocity profiles were recorded at various downstream positions as shown in Figure 6. Notice that as the downstream distance increases to x/d = 100, the value of u'

decreases, corresponding to the decay of the Karman vortex street.
Beyond $x/d = 100$ u' is seen to increase, which can be attributed
to the growth of the secondary vortex street.

Rms velocity profiles were also recorded for the shedding frequency
by using electronic filters. In Figure 7 u'_s profiles are shown for
only those frequencies near f_s, the cylinder's shedding frequency.
Again, as the downstream distance is increased the value of u'_s
decreases, corresponding to the decay of the primary vortex street.
At $x/d > 100$ the velocity fluctuations again rise. This can be
explained by the rise in fluctuations at the first harmonic frequency
of f_w, the secondary or wake frequency. As the secondary street
develops, so also do the fluctuations at a frequency $2f_w$ which is
twice f_w. Although $2f_w$ and f_s are not necessarily _equal_, they
are very close at this particular Reynolds number. Unfortunately, the
filter could not discriminate between fluctuations at f_s and at $2f_w$;
hence a rise in u'_{2w} was recorded also as a rise of u'_s in Figure 7.
This effect is more clearly seen in the spectra of velocity fluctuations
which will be discussed below.

Figure 8 shows rms velocity profiles for a band of frequency near
f_w, the frequency of the secondary vortex street. Profiles up to
$x/d = 75$ were relatively flat and are not shown. As x/d increases
from 75 to 150, however, u'_w is seen to also increase, corresponding
to the growth of the secondary vortex street.

The decay of the primary street and the growth of the secondary
street are in fact exponential in x. This is seen in Figure 9 which
was made by plotting the maximum u' at each downstream profile.

Spectra of the velocity fluctuations at Re = 155 were also recorded as shown in Figure 9.[10] The spectrum at each downstream location was taken at a transverse distance y corresponding to the maximum total rms velocity fluctuations. In the early region of the wake the shedding frequency f_s of 435 Hz has a sharp spectral peak, as do its harmonics. As downstream distance is increased, the amplitude of this spectral peak is seen to decay, corresponding to the decay of u'_s in Figure 7. At a downstream distance of x/d = 75 two new peaks appear at frequencies of 256 and 217 Hz which shall be called f_w , the wake frequency, and $f_{s/2}$, the subharmonic of the shedding frequency, respectively. As x/d is increased further, these two peaks become stronger in amplitude and also tend to merge together to form one broad frequency of approximately 233 Hz. This corresponds to the growth of the secondary vortex street, as was also seen by visualization in Figure 5. At x/d > 75 the first three harmonics of f_w can also be seen in the spectra.

As was discussed previously the value of the wake frequency f_w does not depend explicitly on f_s, the shedding frequency, but rather depends on Reynolds number and the stabiltiy characteristics of the wake profile. The ratio of frequencies f_s/f_w ranges from 1.9 to 5.7 (see Reference 5), and is very close to 2 at Re = 155. The spectra of Figure 10 show the ratio f_s/f_w to be about 1.9.

An attempt was also made to record spectra at a lower Reynolds number such that the ratio f_s/f_w would be much different than 2. However, as seen in the smoke wire photographs, the secondary vortex street is much weaker at Reynolds numbers lower than 156; a peak in

the spectra at the wake frequency was not present, due possibly to the relatively high background turbulence level. Therefore no hot-wire measurements are presented here for Re < 156.

From the flow visualization study, a secondary vortex street could be clearly seen at all Reynolds numbers between 100 and 160. Below Re = 100 no new street was detected, and as seen in Figure 2 at Re = 77, the wake beyond 100 diameters has essentially a parallel wake profile which remains without large scale structures as far downstream as was photographed, i.e., 700 diameters.

Above Re = 160, the cylinder wake begins to become turbulent, as seen in Figure 11 at Re = 167. In photo a), with the wire just downstream of the cylinder, turbulence in the wake appears intermittently, most probably caused by disturbances in the wind tunnel freestream. With the wire further downstream, as in photos b) and c), the wake appears fully turbulent with no clearly identifiable vortex street. However, at much higher Reynolds numbers there again appears to be a larger scale vortex street. The turbulent wake at Re = 650, for example, is shown in Figure 12. Between x/d = 200 and x/d = 250 there is a quite regular array of large structures with a frequency 2 or 3 times lower than that of the original vortex street. This same description holds at the highest Reynolds numbers studied, i.e., Re > 2000, as can be seen in Figure 13. However, hot-wire studies at these high Reynolds numbers did not yield a spectral peak associated with this new large scale structure, again probably due to the relatively high background turbulence level in the tunnel. Spatial averaging techniques might be useful here (see Reference 1).

In addition to circular cylinder wakes, high Reynolds number wakes were also studied behind porous flat plates aligned broadside to the flow. Figure 14 shows smoke-wire photographs of a porous plate with 29% solidity and a Reynolds number of 6800, based on the width of the plate. The vortex street develops from instabilities in the shear layers on the top and bottom of the wake. Far downstream the vortices become unsteady and plenty of small scale structure is seen.

Figure 15 shows a 47% solidity flat plate at Re = 6000. In this case the wake at a few diameters downstream of the plate is fully turbulent. Spectra of velocity fluctuations taken on the centerline and near the edge of the wake are identicle. In this case no instability of the shear layers on the top and bottom of the wake is seen — instead. at approximately 30 diameters an instability of the turbulent wake profile grows into a surprisingly regular vortex street. The significance of this result is that large scale coherent structures have emerged from a fully turbulent wake profile, which initially contained no such structures.

Conclusions

In the wake of a circular cylinder at all Reynolds numbers tested, the shed vortices are seen to decay exponentially within the first 50 to 100 diameters. The cause of this decay is viscous diffusion and the transfer of energy from the vortices to the mean shear. It is thought that the stability characteristics of the mean wake profile are such that structures at the shedding wave number can not persist; the resulting wake profile is essentially void of concentrated vorticity. Smoke-wire flow visualization and hot-wire anemometry have been used

to verify the existence, beyond 100 diameters, of a secondary vortex street in the wake of the cylinder at Reynolds numbers between 100 and 160. Also from flow visualization there appears to be such a secondary street at much higher Reynolds numbers. It is proposed that the new structures results from instabiltiy characteristics of the developing mean wake profile, be it laminar or turbulent. No evidence has been found to support an amalgamation-type process; although the secondary vortex street is strongest when its frequency is approximately half that of the original street.

To support the above conclusion, wakes of porous flat plates were also studied. In the case of a 47% solidity flat plate at a Reynolds number near 6000, the generation of large structures was observed far downstream of the plate which does not initially shed large structures into the wake. The significance of these results is that large scale structures can arise from fully turbulent wake profiles.

Much more research needs to be done in this area, particularly on the three-dimensional character of the wake structures. Perhaps the three-dimensional double roller v rtices reported by Grant [3] at high Reynolds numbers can be explained also by an instability of the turbulent wake profile.

References

1. Wlezien, R.W. "The Evolution of the Low Wavenumber Structure in a Turbulent Wake," Ph.D. Thesis, Illinois Institute of Technology, Chicago, Illinois, December 1981.

2. Townsend, A. The Structure of Turbulent Shear Flow, Cambridge Univeristy Press, 1956.

3. Grant, H.L. "The Large Eddies of Turbulent Motion," JFM 4, Part 2, 149-198 (1957).

4. Taneda, S. "Downstream Development of the Wakes Behind Cylinders," J. Phys. Soc. of Japan, 14, No. 6, 853, (1959).

5. Matsui, T. and Okude, M. "Rearrangement of Karman Vortex Street at Low Reynolds numbers," XVth International Congress of Theoretical and Applied Mechanics, Univ. of Toronto, Aug. 1980.

6. Matsui, T. and Okude, M. "Vortex Pairing in a Karman Vortex Street," Miejo Univ., Yagato, Tenpaku, Nagoya 468, Japan (1981).

7. Corke, T., Koga, D., Drubka, R. and Nagib, H. "A New Technique for Intrducing Controlled Sheets of Smoke Streaklines in Wind Tunnels," Illinois Institute of Technology, Chicago, Illinois 60616 (1977).

Figure 1. Ratio of wavelengths between secondary and primary vortex streets.
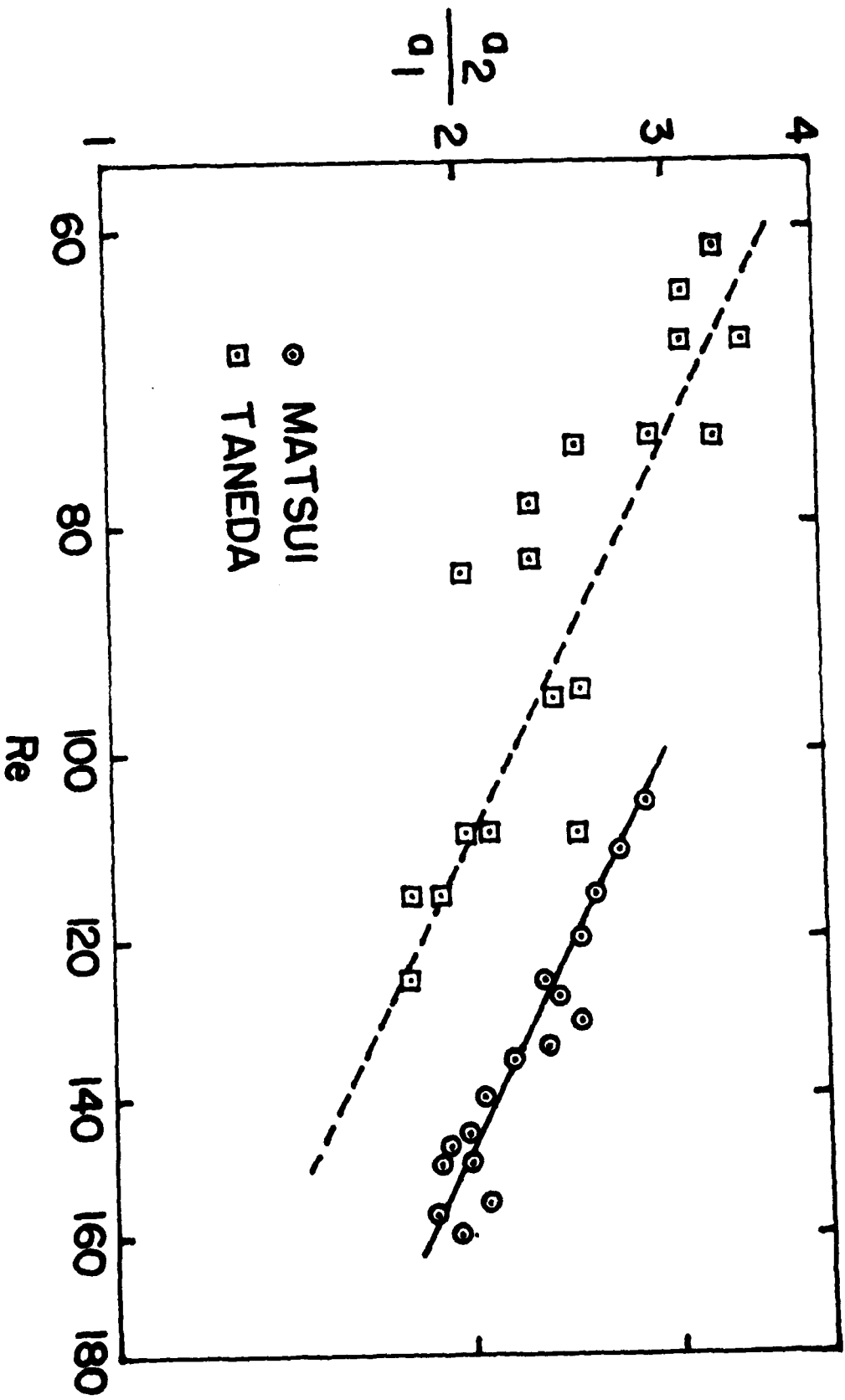
CIRCULAR CYLINDER WAKE
SMOKE WIRE PHOTOGRAPHS

Re = 77

a) wire at x/d = 0
b) wire at x/d = 39
c) wire at x/d = 78
d) wire at x/d = 116
e) wire at x/d = 310
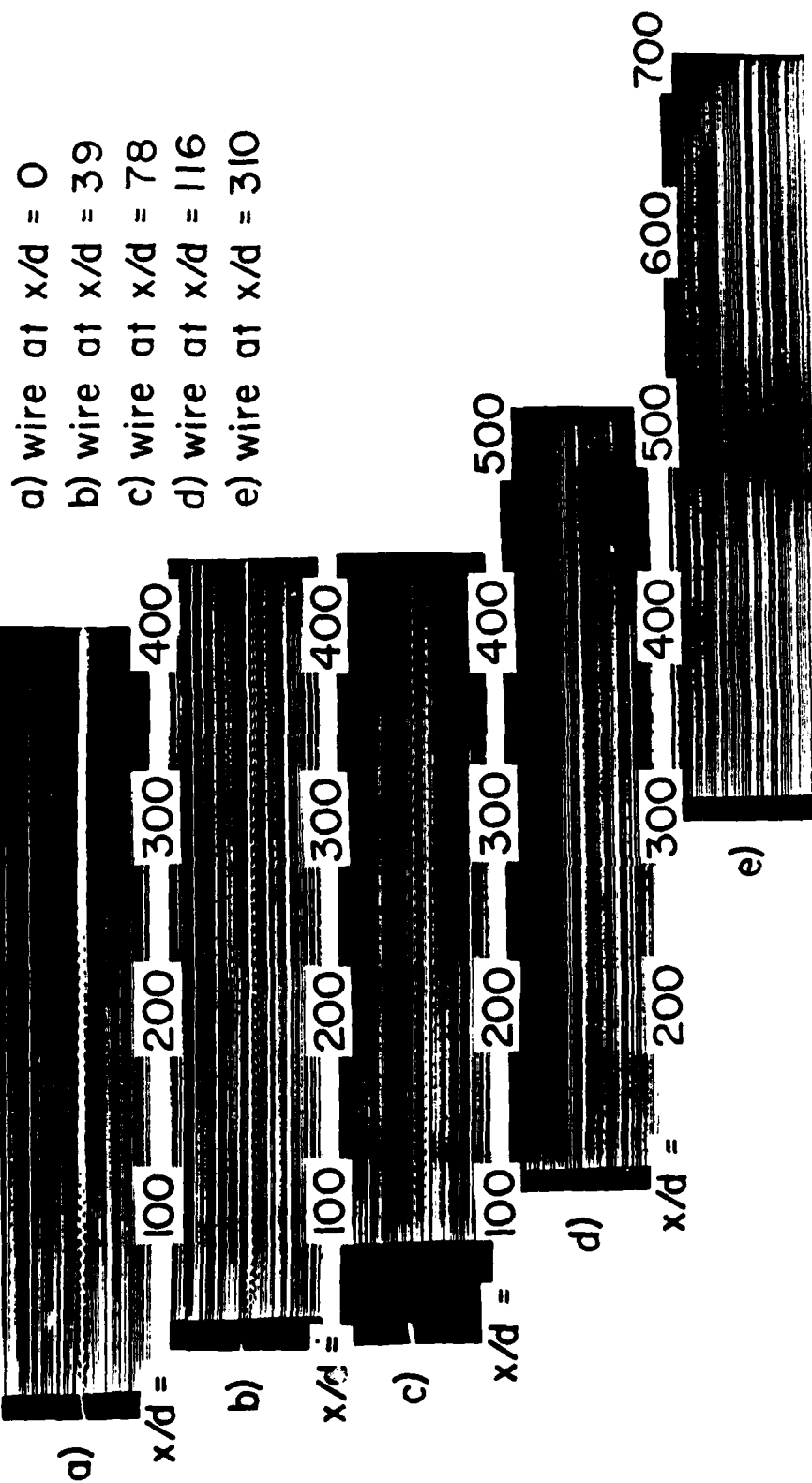
Figure 2. Cylinder wake at Re = 77, decay of Karman vortex street.
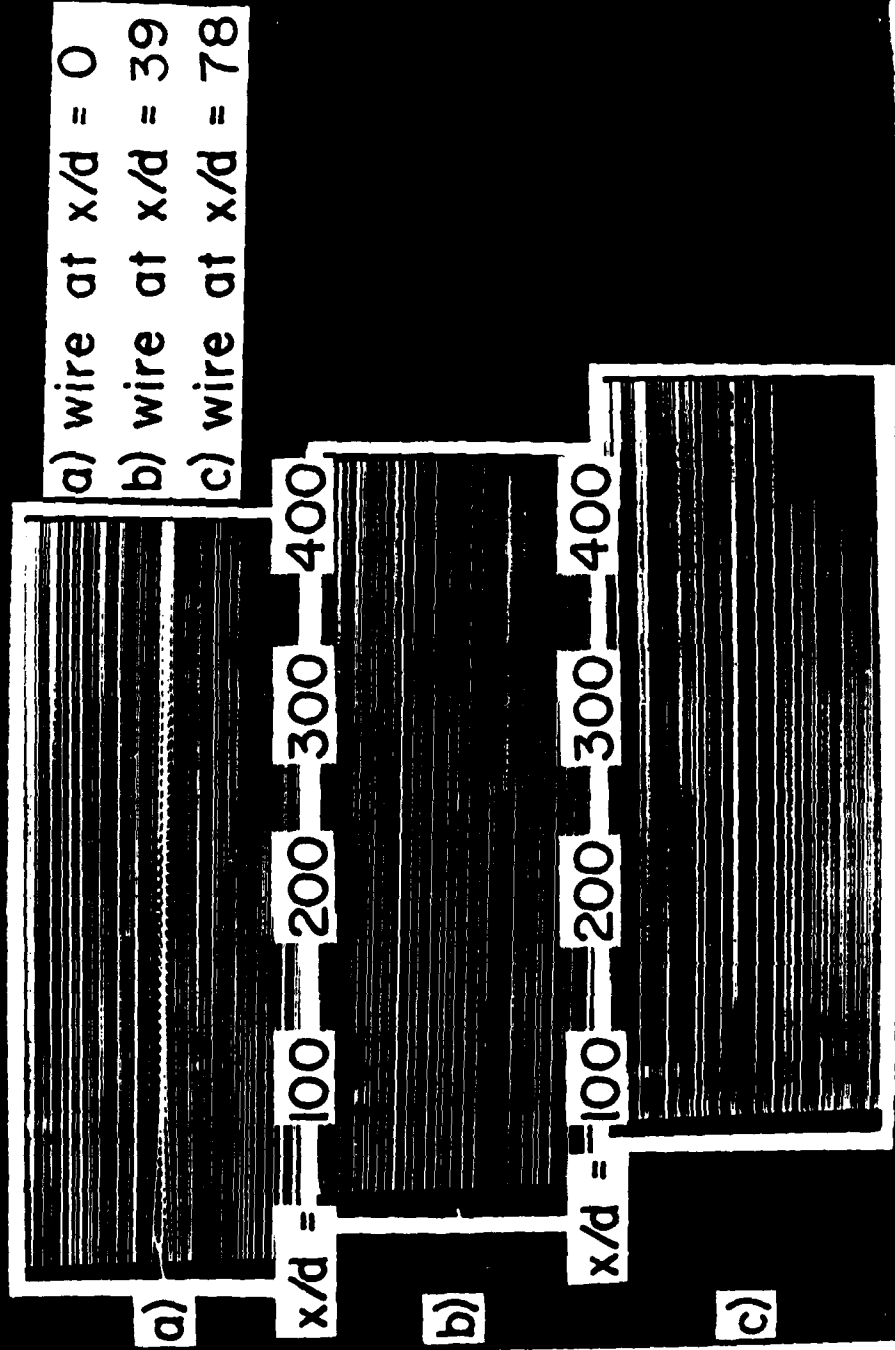
Figure 3. Cylinder wake at Re = 100, appearance of secondary street

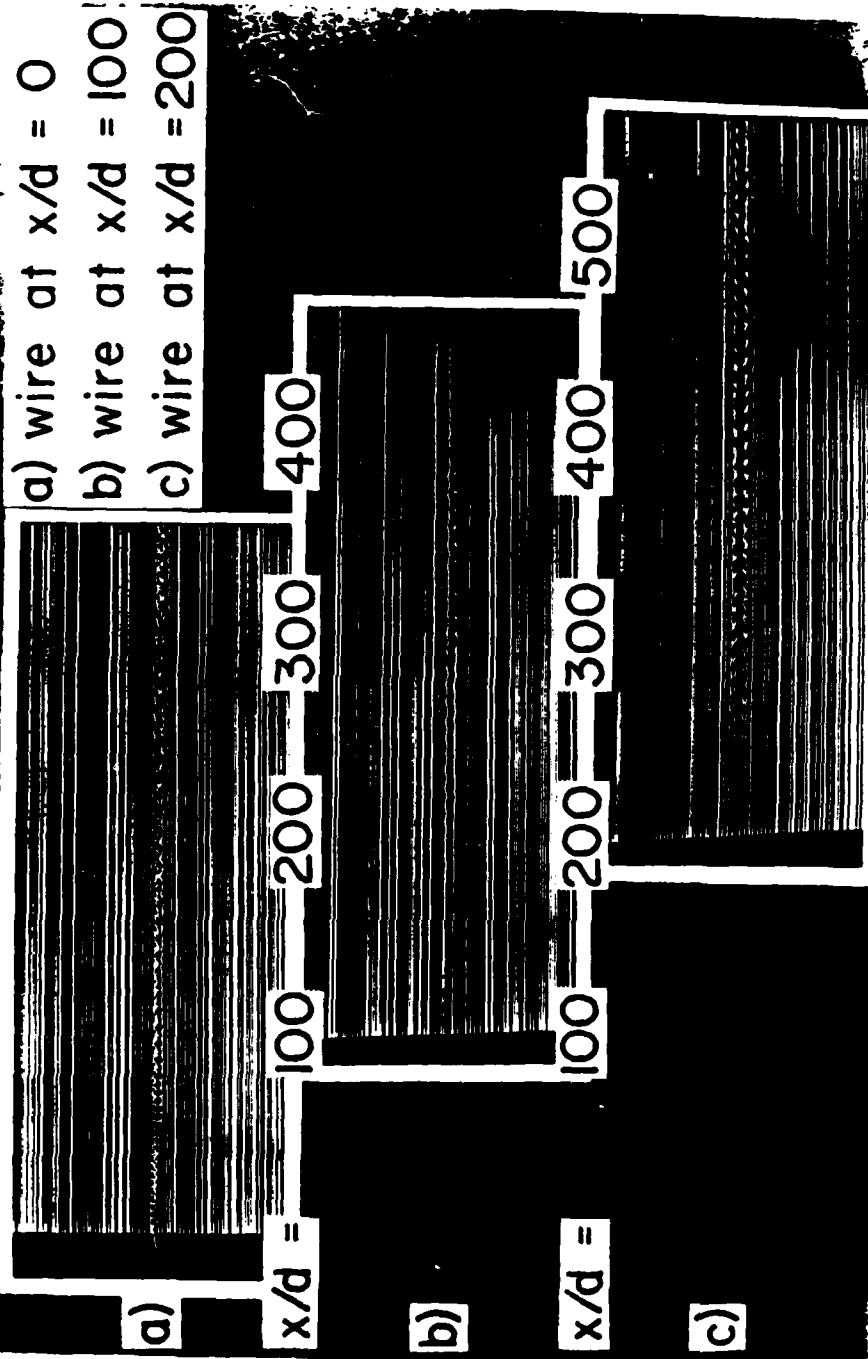CIRCULAR CYLINDER WAKE
SMOKE WIRE PHOTOGRAPHS   Re = 129

a) wire at x/d = 0
b) wire at x/d = 100
c) wire at x/d = 200
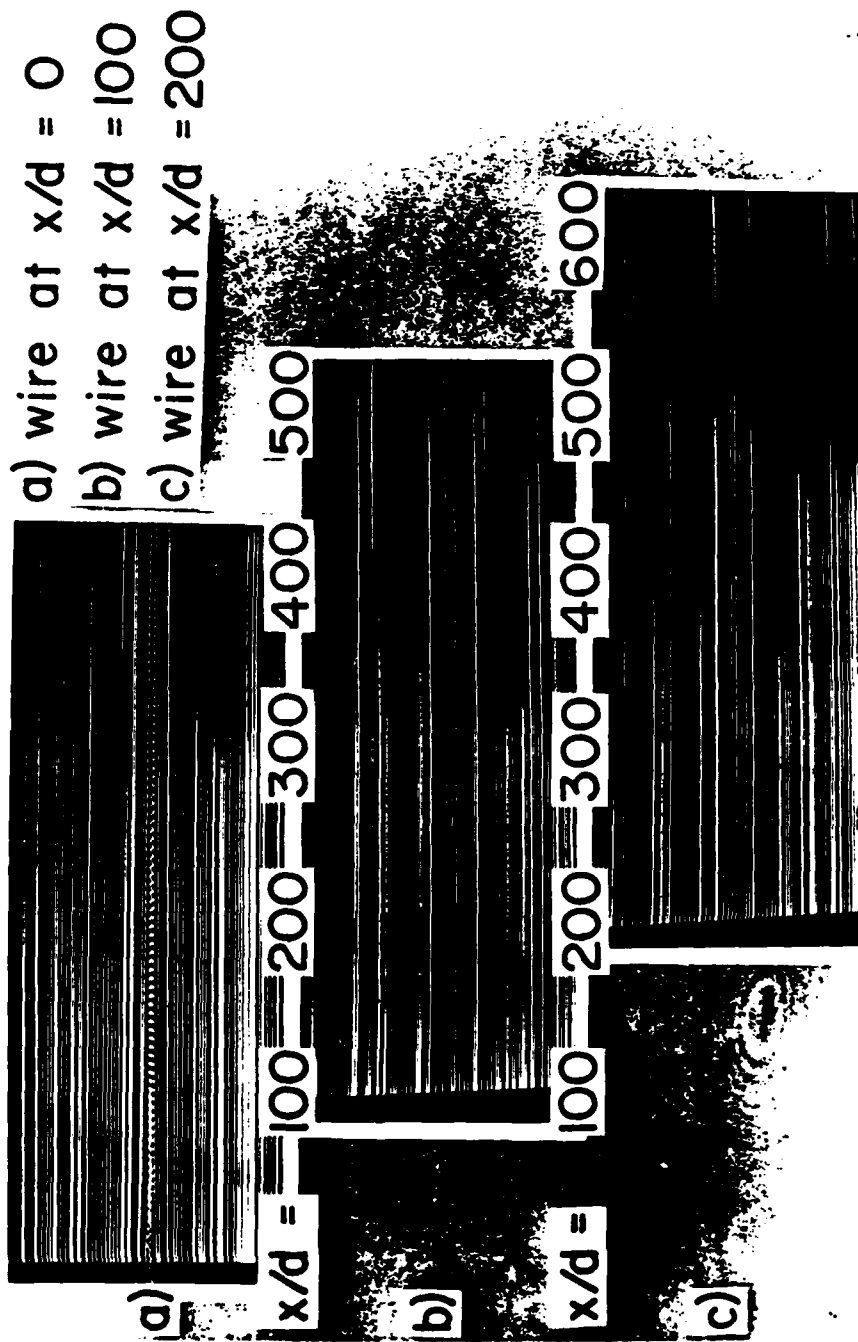
Figure 4. Cylinder wake at Re = 129, appearance of secondary street.

CIRCULAR CYLINDER WAKE
SMOKE WIRE PHOTOGRAPHS

Re = 156

a) wire at x/d = 0
b) wire at x/d = 100
c) wire at x/d = 200

Figure 5. Cylinder wake at Re = 156, appearance of secondary street.
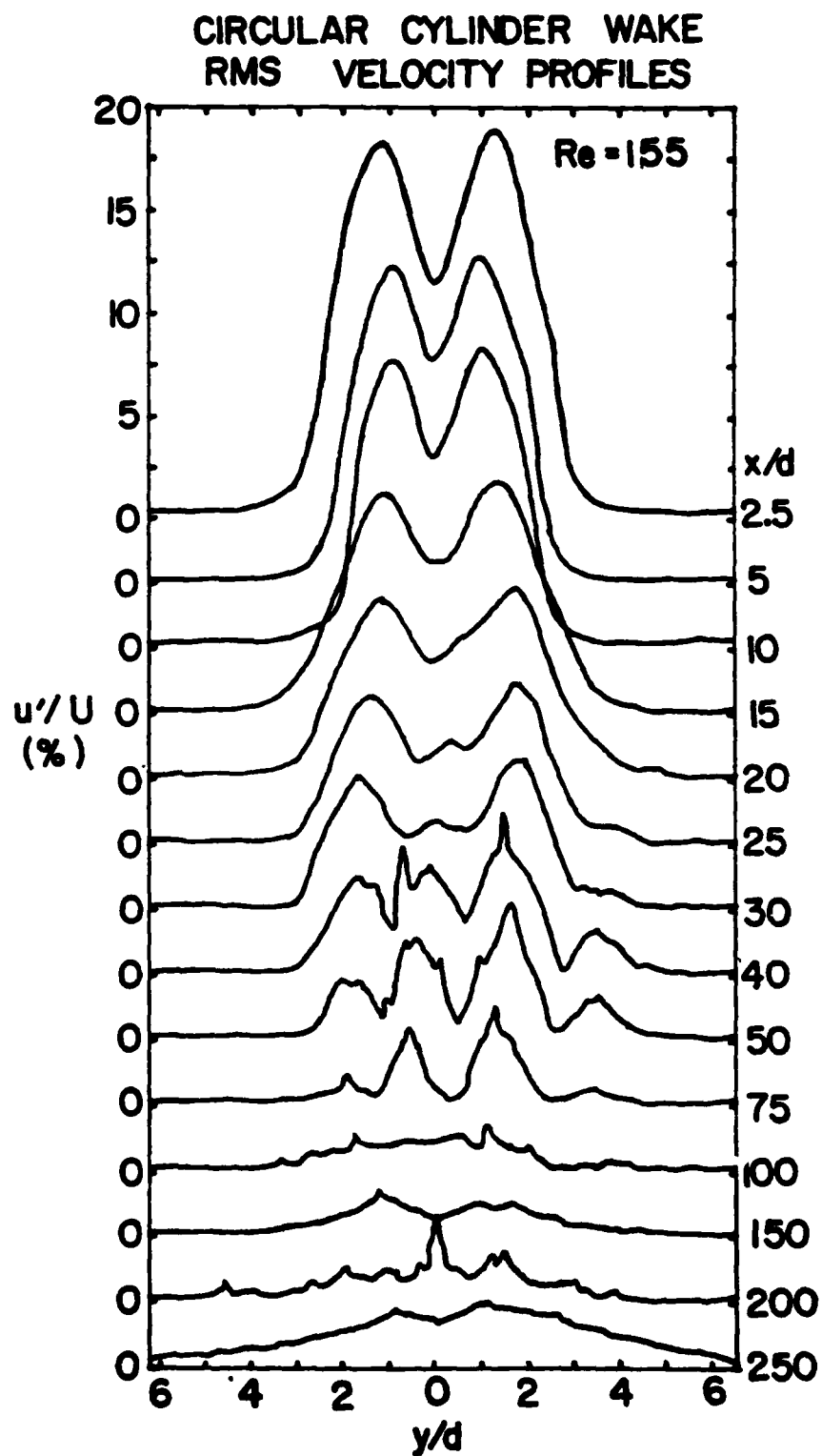
Figure 6.   Cylinder wake at Re = 155, velocity fluctuations
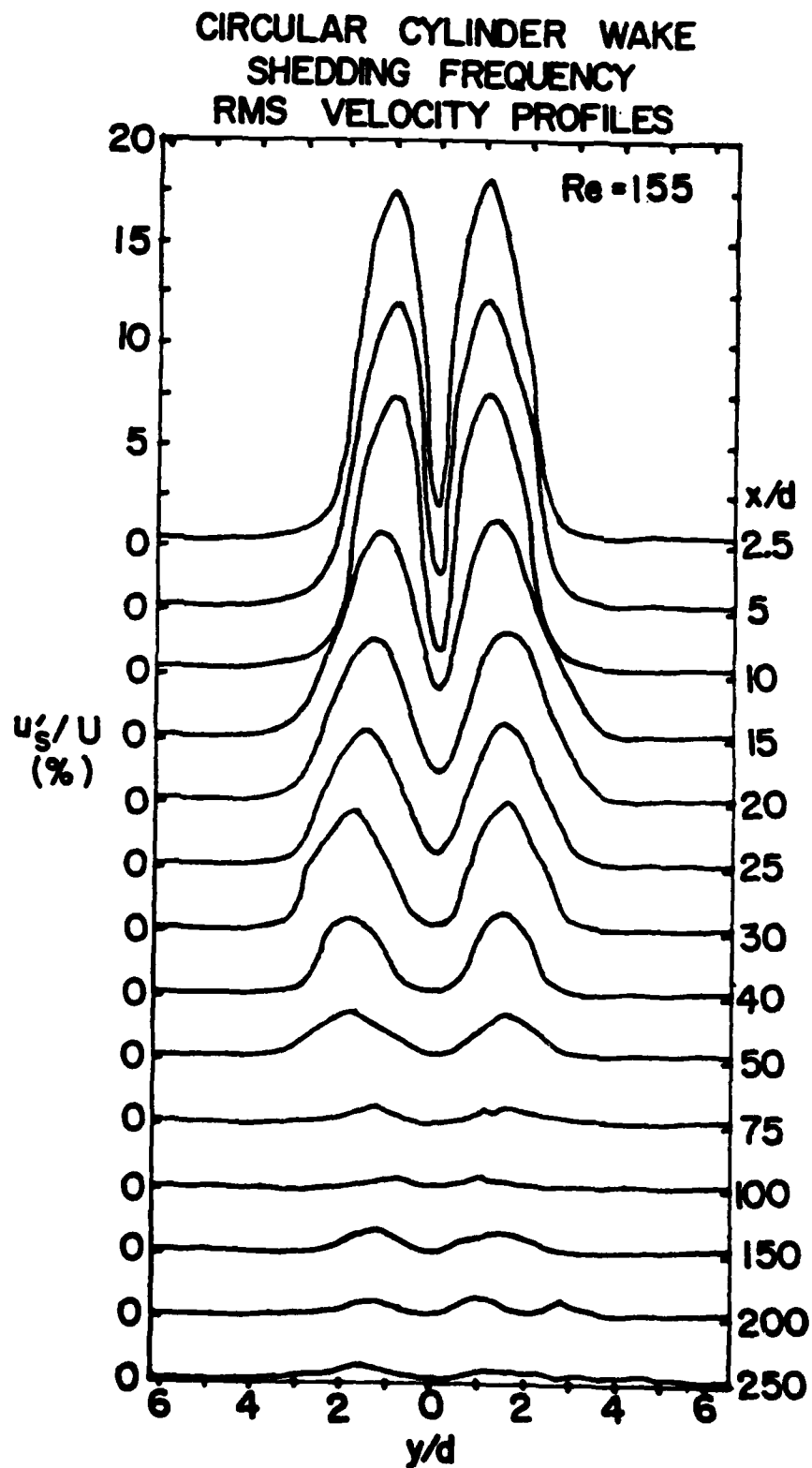
Figure 7. Cylinder wake at Re = 155, velocity fluctuations at the shedding frequency.

Figure 8. Cylinder wake at Re = 155, velocity fluctuations at the wake frequency.

CIRCULAR CYLINDER WAKE
RMS VELOCITY FLUCTUATIONS
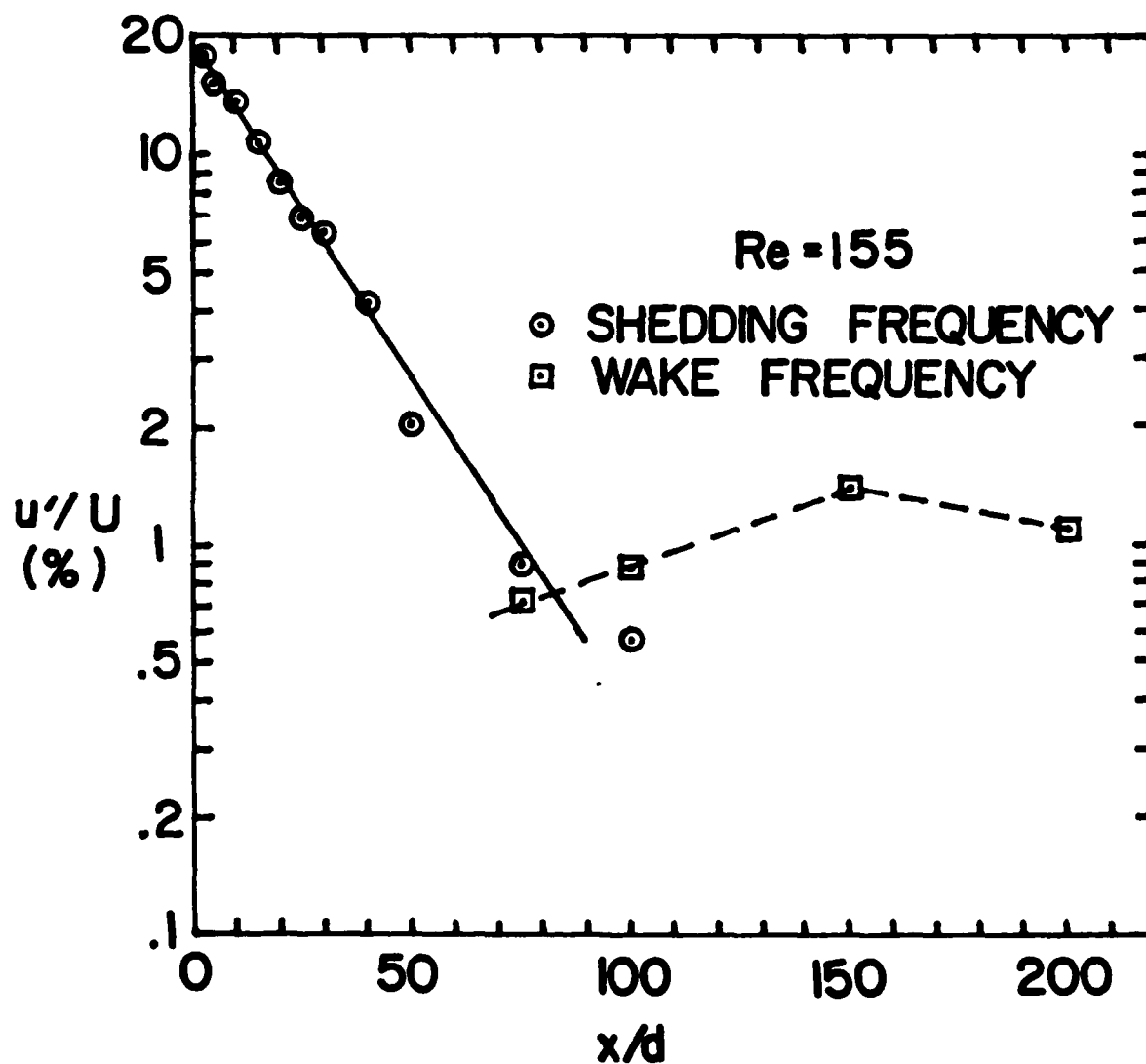
Figure 9.   Cylinder wake at Re = 155, decay of primary street and growth of secondary street.
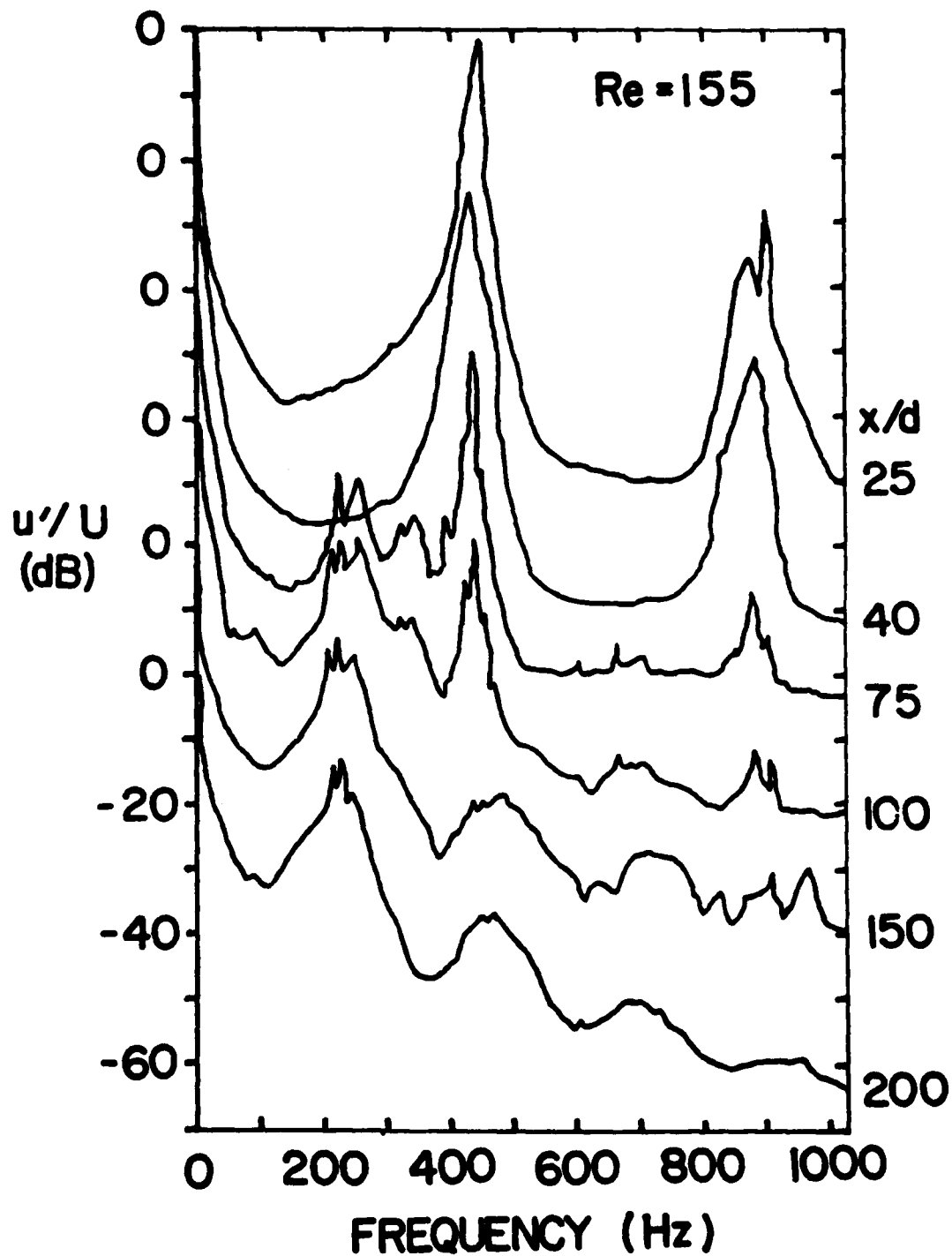
Figure 10. Cylinder wake at Re = 155, spectra of velocity fluctuations.

CIRCULAR CYLINDER WAKE
SMOKE WIRE PHOTOGRAPHS

Re = 169

a) wire at x/d = 0
b) wire at x/d = 100
c) wire at x/d = 200
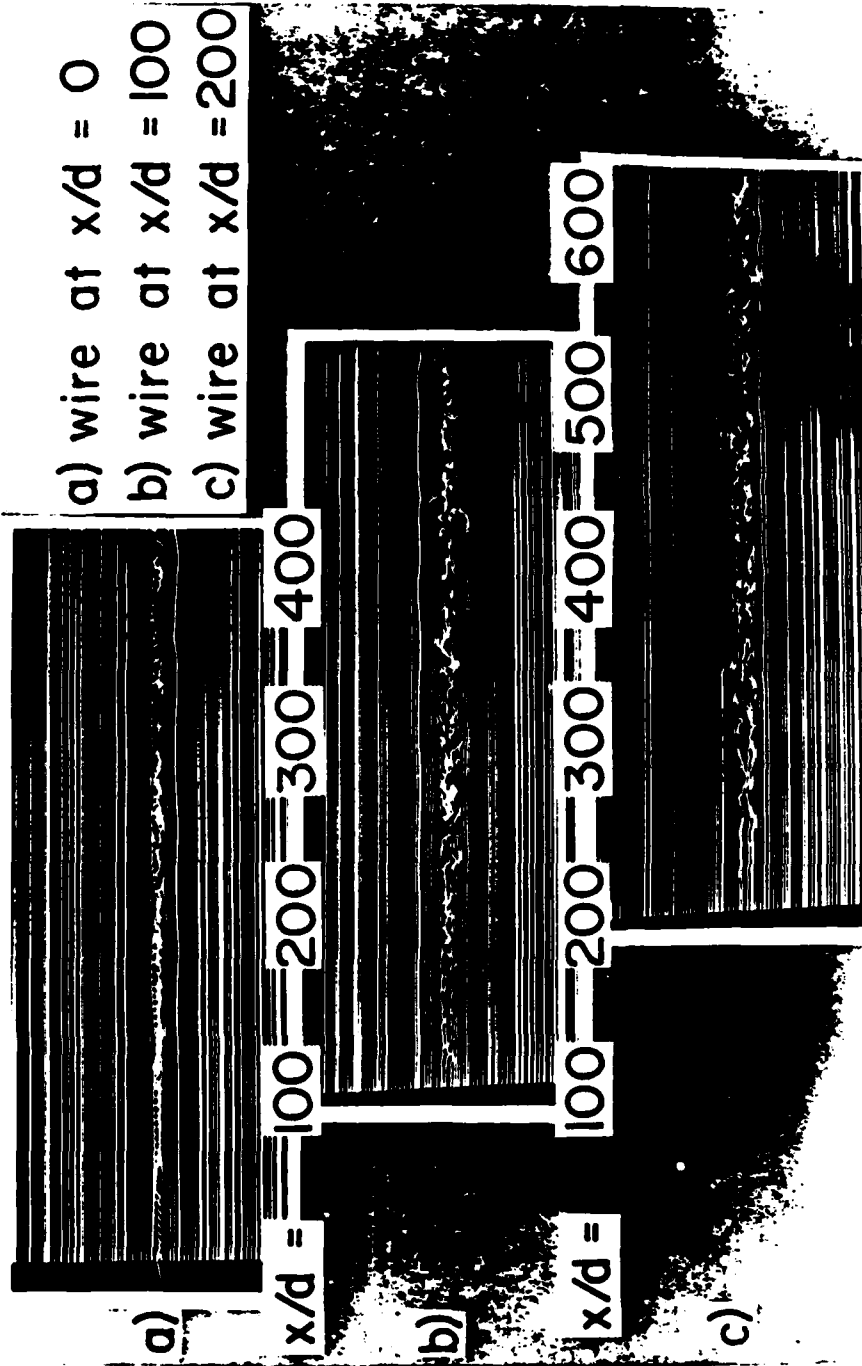
Figure 11. Cylinder wake at Re = 167.

CIRCULAR CYLINDER WAKE
SMOKE WIRE PHOTOGRAPHS

Re = 650

a) wire at x/d = 0
b) wire at x/d = 36
c) wire at x/d = 73
d) wire at x/d = 168

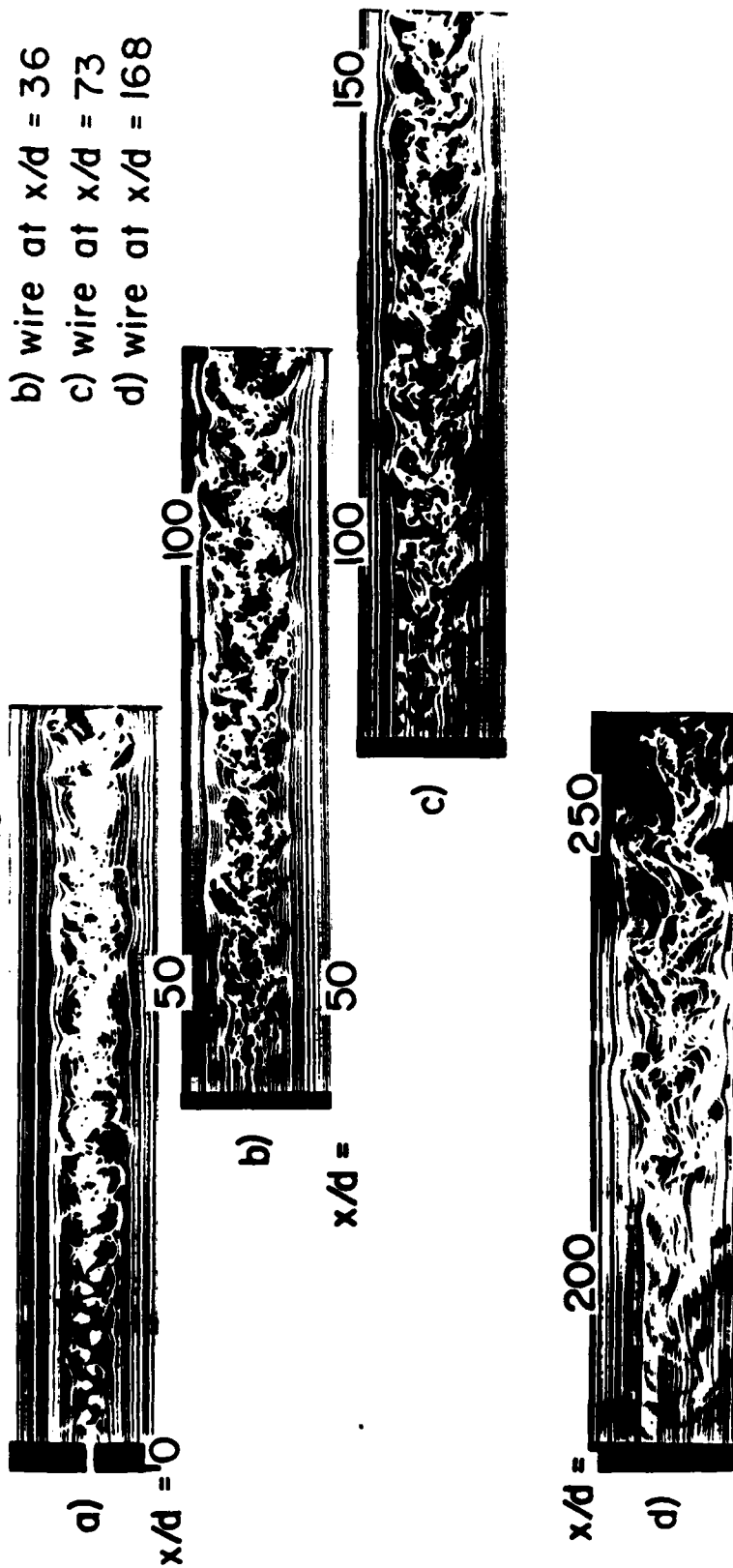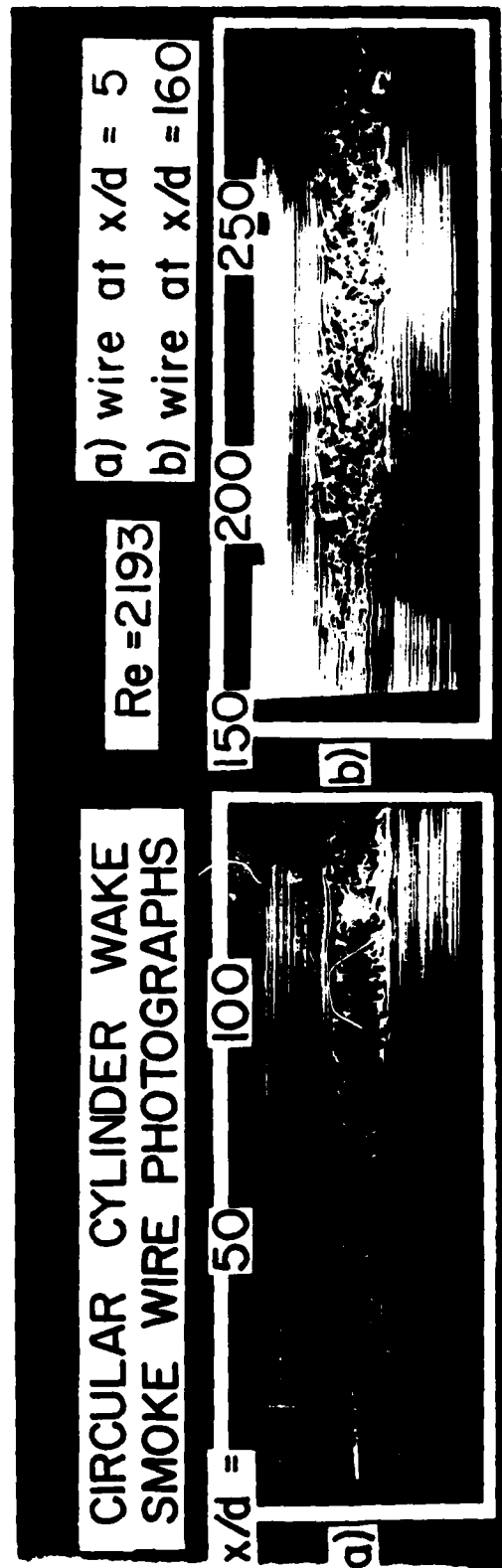Figure 12. Cylinder wake at Re = 650.

Figure 13. Cylinder wake at Re = 2193.

POROUS FLAT PLATE WAKE   Re=6785   a) wire at x/d = 0
SMOKE WIRE PHOTOGRAPHS   29% SOLIDITY   b) wire at x/d = 38

x/d =

10   20   30   40   50   60

a)   b)

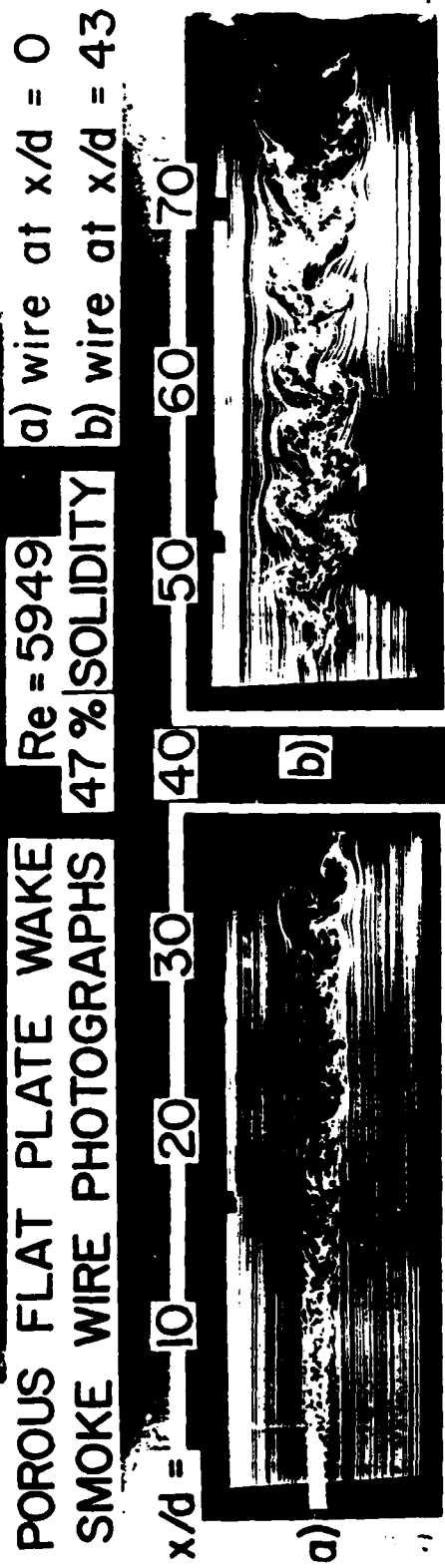Figure 14. Porous flat plate wake at Re = 6785, solidity = 29%.

Figure 15. Porous flat plate wake at Re = 5949, solidity = 47%.